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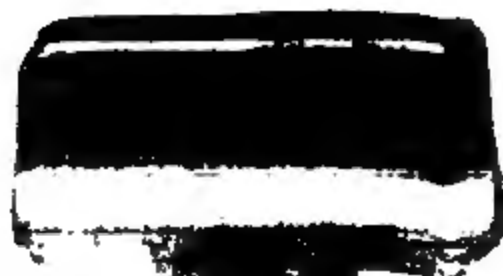
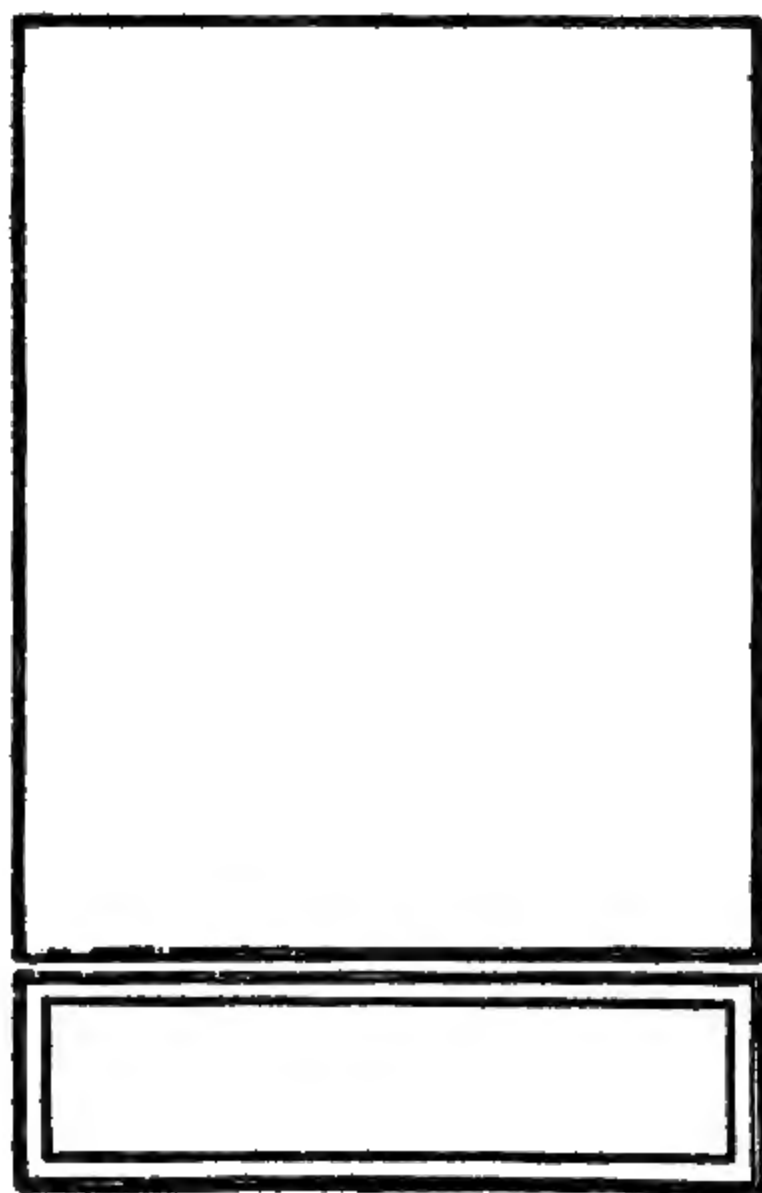
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ELECTRIC TRACTION

ELECTRIC TRACTION:

**A TREATISE ON THE APPLICATION OF
ELECTRIC POWER TO TRAMWAYS
AND RAILWAYS**

BY

A. T. DOVER

A.M.I.E.E., A.A.I.E.E.

**LECTURER ON ELECTRIC TRACTION AT THE BATTERSEA
POLYTECHNIC, LONDON**

With 518 Illustrations and 5 Folding Plates

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P R E F A C E

THIS book is intended for Engineers and advanced students : it treats of the principles relating to the application of electric power to tramways and railways. Representative examples of modern tramway and railway practice are included, but detailed accounts of electrifications have been omitted, as the latter are treated fully in the technical press. The bibliography in Appendix III. indicates where information relating to the principal electrifications can be obtained.

Generating stations and transmission lines have not been considered, as these could not have been adequately dealt with in the present volume. Moreover, the generation of electrical energy is now a specialised subject and involves considerations which have little bearing on the utilisation of the energy for traction purposes.

The subject matter has been arranged as follows :—Mechanics of train movement ; motors ; control ; auxiliary apparatus ; rolling stock ; detailed study of train movement ; track and overhead construction ; distributing systems and sub-stations. A number of worked examples have been included in the text, and a collection of 67 examples, taken principally from public examination papers and covering the whole scope of the subject, is given at the end of the volume.

The diagrams in the chapters on “ control ” have been made as clear as possible : the tracing of control circuits, however, requires practice, and this is best acquired by the study of simplified diagrams such as are given at appropriate places in the text.

The author is under considerable obligation to many engineers and manufacturers who have generously supplied him with data, drawings, photographs, etc. Among the former are :—Mr. John A. F. Aspinall, General Manager, Lancashire and Yorkshire Railway ; Mr. W. A. Agnew, Chief Mechanical Engineer, London Underground Railways ; Mr. Philip Dawson, Consulting Engineer to the London, Brighton, and South Coast Railway ; Mr. A. L. C. Fell, Chief Officer, London County Council Tramways ; Mr. Herbert Jones, Chief Electrical Engineer, London and South-Western Railway ; Mr. William S. Murray, Consulting Engineer to the New York, New Haven, and Hartford Railroad ; Mr. C. W. Mallins,

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In many cases data and particulars of electrifications have been drawn from the technical press, acknowledgments of which have generally been made in the text. The chief sources of such information have been :—*The Tramway and Railway World*, *The Electrician*, *The Electrical Review*, *The Engineer*, *Engineering*, *The Electric Railway Journal*, *The Electric Journal*, *The General Electric Review*, *L'Éclairage Électrique*, the publications of the Engineering Standards Committee, and the *Proceedings* (and *Transactions*) of the following Institutions :—The Institution of Electrical Engineers, The American Institute of Electrical Engineers, The Institution of Civil Engineers, The Institution of Mechanical Engineers. To these the author desires to express his indebtedness.

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To the Senate of the University of London, the Examinations' Board of the City and Guilds of London Institute, and the Council of the Institution of Electrical Engineers, the thanks of the author are due for permission to use questions from their examination papers.

The author wishes to take this opportunity of expressing his appreciation of the valuable assistance—in the form of suggestions, criticisms, MS.- and proof-reading—given him, during the preparation of the work, by his colleagues Dr. A. W. Ashton, M.I.E.E. ; Messrs. J. Beaumont Shaw, A.R.C.S. ; and William Thomson, M.A.

A. T. D.

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LIST OF SYMBOLS

- A = Cross-sectional area of coach.
 a = Cross-section of wire.
 \quad = Ratio $\frac{\text{total field turns}}{\text{armature turns between brushes}}$.
 α = Acceleration in ml.p.h.p.s.
 \quad = Coefficient of linear expansion.
 B = Flux density (B_m = maximum flux density).
 \quad = Portion of capital cost of cable which is dependent on the cross-section.
 b = Ratio $\frac{\text{synchronous speed in r.p.m.}}{\text{speed of rotation of armature in r.p.m.}}$.
 β = Braking retardation in ml.p.h.p.s.
 β_c = Coasting retardation in ml.p.h.p.s.
 c = Number of circuits in armature winding.
 D = Distance (in miles) between stops.
 \quad = Diameter of armature, wheel, or trolley-wire.
 \quad = Distance between conductors of circuit.
 D' = Distance (in miles) from start to cut-off.
 Δ = Radial depth of air-gap.
 \quad = " Delta " connection of three-phase circuits.
 δ = Sag of trolley-wire (or catenary wire)
 E = Counter E.M.F. generated in armature or stator winding.
 \quad = Terminal E.M.F.
 E_d = Dynamic E.M.F. in armature of repulsion motor.
 E_s = Static (transformer) E.M.F. in armature of repulsion motor.
 E_x = External E.M.F. for doubly-fed motor.
 e = Pressure drop due to resistance.
 e_d = Compensating E.M.F. in exciting circuit of compensated-repulsion motor.
 e_l = E.M.F. of self-induction in exciting circuit of compensated-repulsion motor.
 e_t = Transformer-E.M.F. induced in armature coils short-circuited by brushes.
 η = Efficiency.
 F = Force or tractive-effort.
 f = Frequency of supply current (cycles per second).
 f_1 = Frequency in armature or rotor.
 Φ = Flux per pole in megalines (Φ_m = maximum flux).
 Φ_e = Excitation flux in repulsion motor.
 Φ_t = Transformer flux in repulsion motor.
 Φ_s = Stator flux in Déri motor.
 ϕ = Phase angle between current and E.M.F.
 G = Gradient in per cent.
 γ = Gear ratio.
 h = Number of hours per annum cable is in service.

- I = Current.
 i_m = Magnetising current.
 K, k = Constants.
 k = Radius of gyration.
 = Air-resistance coefficient for shape of end of train.
 = Ratio of transformation.
 L = Length (in feet) of train or coach.
 = Length of trolley-wire per span.
 = Inductance.
 l = Half length of span.
 λ = Ratio $\frac{\text{exposed transverse surface of coach}}{\text{cross-section of coach body}}$.
 = Spacing of droppers in catenary suspension.
 M = Torque.
 m = Number of armature coils short-circuited by a brush.
 = Percentage interest and depreciation charges on capital cost of completed cable.
 μ = Permeability.
 n = Revolutions per minute of armature or rotor.
 = Percentage interest and depreciation charges on capital cost of booster set.
 n_s = Synchronous speed in revolutions per minute.
 P = Power at driving axles of train.
 = Pull on poles in span-wire construction.
 p = Number of poles.
 = Price (in pence) of one kilowatt-hour delivered to cable.
 Q = Specific electric loading (ampere-turns per inch of periphery of armature).
 R, r = Resistance in ohms.
 R = Total train resistance in lb.
 = Radius of curves in ft.
 r = Specific train resistance in lb. per ton.
 = Radius of wire.
 S = Longitudinal exposed surface of coach.
 S, s = Speed in ml.p.h.
 s = " Slip " of rotor of induction motor.
 = Half length of span of span-wire.
 σ = Dispersion coefficient for induction motor.
 T = Running time in seconds.
 = Number of turns in series between brushes (or per phase).
 = Tension in trolley-wire (or catenary wire) at lowest point.
 t = Time in seconds.
 = Turns per coil of armature winding.
 θ = Temperature.
 U = Hypothetical speed of train.
 V = Speed of train or car in ml.p.h. (V_m = maximum speed).
 = Terminal voltage.
 v = Average speed of train or car in ml.p.h.
 W = Dead weight of train in tons.
 = Weight per span of trolley-wire (or span-wire).
 W_e = Effective (or accelerating) weight of train in tons.
 w = Weight per foot of trolley-wire (or span-wire).
 X, x = Reactance.
 X = Capital cost (in £) of booster per kw. output.
 Y = Cost (in £) of attendance and maintenance on booster per kw. output per annum.
 y = Deflection at dropper in catenary suspension.

z = Distance between trolley-wire and catenary wire at mid-span.
 = Impedance.

ζ = Ratio $\frac{\text{Effective weight of train}}{\text{Dead weight of train}} \left(= \frac{W_e}{W} \right)$.

NOTES.—**Logarithms**, where used, are to the base 10.

Vector Diagrams.—All diagrams have been drawn for *clockwise* rotation.

E.M.F. vectors are represented by an ordinary arrow-head.

Flux vectors are represented by a double arrow-head.

Ampere-turn vectors are represented by a solid arrow-head.

Current vectors are represented by a closed arrow-head.

Circuit Diagrams of Single-phase Motors.—These diagrams have been drawn for a ring armature winding. The magnetic axis of the armature coincides with the axis of the brushes. With regard to the stator windings—

E represents an exciting winding ;

N represents a neutralising or compensating winding ;

C represents a commutating-pole winding. •

Weights.—The British ton (2240 lb.) is used throughout this treatise. All weights relating to Continental and American machines and apparatus have been reduced to this unit.

LIST OF ABBREVIATIONS

Amperes	amp.
Electro-motive force	E.M.F.
Foot, feet	ft.
Horse-power	H.P.
Inch	in.
Kilometre	kM.
Kilowatt	kw.
Kilowatt-hour	kw.h.
Mile	ml.
Miles per hour	ml.p.h.
Miles per hour per second	ml.p.h.p.s.
Millimetre	mm.
Pound	lb.
Revolutions per minute	r.p.m.
Second	sec.
Watt hour	wh.
Watt hours per ton mile	wh./t.ml.

ELECTRIC TRACTION

CHAPTER I

INTRODUCTION

THE considerations involved in the application of electric power to the working of tramways and railways may be divided into two classes—(1) technical, (2) financial. In the present volume we shall confine our attention to the former.

The **technical considerations** involve the supply of electric power from a generating station to a number of cars or trains which have to operate, over a given track, to a given schedule.

With tramways, the **system of operation** and the operating voltage are prescribed by the Regulations of the Board of Trade (see Appendix I), but with railways a choice of systems and voltages (subject to the approval of the Board of Trade) is possible. Thus tramcars must be supplied with continuous current at a voltage not exceeding 550 volts. On the other hand, railway trains may be supplied with either continuous or alternating current, at low or high voltage.

The **methods of supplying power to cars operating on tramways** are as follows :

(1) The **Overhead system**. An overhead conductor, fed from the generating station at suitable points, is suspended above the track, and current is conveyed from this conductor to the car equipment by means of a suitable current collector—in the form of a trolley wheel or a sliding bow—carried on the car. The track rails are utilised as the return conductor, and are connected to the generating station at suitable points.

In some very special cases, however, the return conductor is placed overhead,* and two current collectors are required.

(2) The **Conduit system**. Two conductors of opposite polarity, fed from the generating station at suitable points, are supported in a slotted conduit—located either in the centre or at the side of the track—and the current is conveyed from these conductors to the car equipment by means of a current collector, which is carried on the car and passes through the slot in the conduit. Generally, both conductors are supported from insulators, and the track rails do not form part of the

* The only example, in this country, of an insulated return for overhead tramways occurs on a section of the London County Council tramways in the neighbourhood of Greenwich Observatory.

conducting system. The conductors in the conduit consist of T-rails arranged thus, —|—.

(3) The **Surface-contact system**. An insulated cable, supplied with power from the generating station, is placed underground adjacent to the track, and is connected at frequent intervals to insulated contact studs, which are located in the centre of the track, and project slightly above the road surface. The upper portion of each stud is connected to the cable through an automatic switch, which is arranged so that it is only closed when a car is over the stud. The current is conveyed from the studs to the car equipment by means of a skate collector carried under the car just above the road surface, the length of the skate being slightly greater than the distance between consecutive studs. The track rails are utilised as the return conductor.

Of these systems, the conduit system is the most expensive: * consequently, it can only be adopted in large cities or in other cases where the overhead and surface-contact systems are unsuitable.

Examples of the conduit system are to be found in London, Bournemouth, Paris, New York, Washington, and Brussels. In this country the conduit lines of the London County Council tramways form the largest installation of the conduit system, and comprise 122 miles of route, of which 117·5 miles are double track.

The first cost of the overhead and surface-contact systems may be considered as approximately equal (see footnote). The surface-contact system has an advantage from the æsthetic standpoint, but its operation depends on the satisfactory working of a large number of switches (which may exceed 500 per mile of single track). It is apparent, therefore, that this system would be wholly unsuitable for an extensive tramway undertaking. Although numerous schemes for operating the switches have been proposed, only a very few have been commercially satisfactory. At the present time there are only two examples (comprising a total of 16 miles of route) of the surface-contact system in operation in this country, and there is no tendency towards future development. On account of these features we shall not consider further details of the system.†

The overhead system has been adopted on an extensive scale for tramways and railways in this country and abroad. At the present time (1916) there are, approximately, 2500 (route) miles of tramways in the United Kingdom operating on this system.

During the last few years, the overhead system has been adapted for the supply of power to electric omnibuses (called "railless cars"). This system of "**railless traction**" possesses advantages over tramways

* The comparative costs of the conduit, overhead and surface-contact systems average as follows:

	Per Mile of Single Track.
Conduit system (including special work, pipe diversions, &c.)	£17,000
Overhead system (including special work, pipe diversions, &c.)	9,300
Surface-contact system (including special work, pipe diversions, &c.)	9,700

It must be noted, however, that, in every system, the cost of construction varies greatly, according to the nature of the obstructions and the extent of special work.

† A description of one of the surface-contact systems in operation in this country will be found in a paper by Mr. Stanley Clegg on "The Griffiths-Bedell System from a Tramway Manager's Point of View." See *Journal of the Institution of Electrical Engineers*, vol. 42, p. 473.

in that the large expense of the installation and maintenance of the track is avoided.* Consequently, the system can be utilised as an extension of an existing tramway system to outlying villages which require only an infrequent service of cars. The railless system is also suitable for towns having narrow streets, and in these cases it has obvious advantages over tramways, since railless cars can thread through the traffic. On the other hand, railless cars are necessarily smaller and lighter than the majority of tramcars, while the amount of power required by a railless car is greater than that which would be required by a tramcar of equal weight, on account of the increased resistance to motion.

The overhead equipment for railless cars must, obviously, comprise two conductors of opposite polarity, and the current collector must allow the cars to be piloted through the traffic.

The railless system of electric traction has been adopted in conjunction with several tramway systems in this country and the Continent. Examples will be found in Leeds, Bradford, Stockport, Aberdare, Dundee.

The methods of supplying power to railway trains comprise (1) the overhead system, (2) the conductor rail system.

The overhead system must, obviously, be adopted when the trains are supplied at high voltage. Under these conditions heavy trains may be supplied through conductors of relatively small cross-section, and the collection of the current required by a heavy train can be performed satisfactorily by a collector of the sliding bow type. Overhead construction is universal for all alternating-current railways, and it is also adopted for continuous-current railways operating at voltages above 1500 volts. In all these cases the track rails are utilised as the return conductor, so that with continuous-current and single-phase systems only one overhead wire is required for each track.

The conductor rail system is adopted for heavy electric traction systems operating at voltages up to about 1200 volts, since, in these cases, large currents may be required by the trains. The power is supplied to the trains through high conductivity steel rails, which are supported on insulators parallel with the track rails and fed at suitable points from the generating station or from sub-stations. The current is conveyed from the conductor rails to the train equipment by means of collector shoes. In some cases the track rails are used as the return conductor, so that only one conductor rail is required.

Railway electrification in this country has been confined to the urban and suburban lines in the vicinity of our large cities (*e.g.* London, Liverpool, Newcastle, Manchester). In the United States of America and on the Continent electrification has been carried to trunk lines and also to freight lines operating in mountainous districts.

The chief difficulties in the way of electrification of our trunk lines are: first, the existence of the modern steam locomotive; and, second, the large cost of converting the lines from steam to electric operation. The modern steam locomotive in service on our trunk lines is capable of fulfilling all the requirements of the traffic department for fast passenger

* The cost of laying double track for tramways is, approximately, £12,000 per mile of route; and the cost of the overhead equipment, including the feeders and ducts, is, approximately, £3700 per mile of route.

traffic. An electric locomotive capable of performing similar services could be built, but this locomotive would have to show marked economies in power consumption and operating expenses in order to warrant the large cost of the change-over. The case is entirely different with suburban railways. On these railways, large numbers of passengers have to be transported daily over relatively short distances in competition, in many cases, with other methods of transportation. For the railway to retain its traffic and create additional traffic, the passengers must be transported over a given distance in a much shorter time than that required by its competitors.

Now, the frequent starting and stopping of steam trains at stations spaced a short distance apart does not lead to economical operation,* and, moreover, it is impossible to obtain high schedule speeds unless exceptionally heavy locomotives are adopted. On the other hand, an electric train is capable of handling such a service economically at a fairly high schedule speed. The schedule speed with electric operation may be from 50 to 100 per cent. higher than that corresponding to steam operation; this increase being due to the higher acceleration of the electric train. Since the electric train is capable of running the service at a higher schedule speed, it follows that the train miles which can be run with a given equipment in a given time are greater with electric service than with steam service. A given number of electric trains is therefore capable of dealing with a greater volume of traffic than the same number of steam trains with equal seating accommodation. The electric train has the additional advantage that it may be divided and run in sections during the periods of light traffic, thereby enabling a frequent service of trains to be maintained, leading to increased traffic during these periods.

Electric traction also forms a solution to the problem of relieving congestion at terminal stations. Thus the number of trains which can be got into and out of a terminus in a given time depends on the number of signal and train movements required. With electric trains consisting of motor-coaches, the number of signal and train movements required for a train entering and leaving a terminus is only one-fourth of the number required for a steam train. Now the number of trains which can be run over the tracks in a given time is limited by the terminal facilities. It is obviously more desirable to increase these facilities by adopting electric traction than by the alternative of carrying out the widening of the tracks and the extensions and additions to the station platforms, since the electric train service will, in most cases, lead to additional traffic, the revenue from which will go towards meeting the cost of electrification.

Electric traction also possesses advantages over steam traction for the handling of freight traffic, particularly on railways having heavy gradients and long tunnels. In deciding upon the system of electrification to be adopted for a railway with heavy gradients, consideration would naturally be given to those systems in which electric regenerative braking could be used. The trains descending the gradients would be braked electrically, so that, instead of the kinetic energy of the train being dissipated in the brake shoes and wheel tyres, it would be con-

* In this connection see Mr. J. A. F. Aspinall's Presidential Address to the Institution of Mechanical Engineers, *Proceedings of the Institution of Mechanical Engineers* (1909), pp. 423-488.

verted into electrical energy and returned to the supply system. Thus, in addition to the saving in the power consumption, the maintenance of the brake shoes, wheel tyres, and track rails would be reduced. The reduction in the latter items alone may be sufficient to cover a fair percentage of the costs of electrification.

The systems available for the electrification of railways are—(1) the continuous-current system, (2) the single-phase alternating-current system, and (3) the three-phase alternating-current system.

Each of these systems possesses characteristic features. Thus, the three-phase system may be called a *constant-speed* system, while the continuous-current and single-phase systems may be called *variable-speed* systems (since a change in the tractive effort is accompanied by a change in the speed). The continuous-current system, however, may also be designed to operate with a constant-speed characteristic.

With reference to the **operating voltages** of these systems :

Continuous-current equipments must be built for operation at the line voltage, but alternating-current equipments can be supplied through a transformer (carried on the train) at any voltage desired. The alternating-current systems, therefore, allow the use of a high-voltage line. On account of the duplication of the overhead conductors for the three-phase system, the line voltage cannot be raised to the same limits as in the single-phase system.

Continuous-current railways may be classed as *low voltage*, or *high voltage*. In the former case, the operating voltage does not exceed 750 volts, while in the latter case the operating voltage exceeds 750 volts, and may reach 5000 volts.* At the present time there are high-voltage continuous-current railways in operation on which operating voltages of 1200, 1500, 2400, and 3000 volts are adopted.

The operating voltage of single-phase railways is, generally, between 6000 and 15,000 volts. The frequency is either 15, 16½, or 25 cycles.

The operating voltage of three-phase railways is generally between 3000 and 6000 volts. The frequency is usually either 15 or 16½ cycles, although, in some cases, a frequency of 25 cycles has been adopted.

On account of certain features of single-phase motors (which are discussed later), **composite alternating-current continuous-current systems** are now being developed, in which the advantages of the single-phase transmission system and overhead construction are combined with the advantages of continuous-current and polyphase motors. Thus the high-tension single-phase supply current may be converted into three-phase current by means of a phase converter,† or it may be rectified by means of a mercury-vapour rectifier. In the former case the driving motors are of the polyphase induction type, and regenerative braking is practicable; while in the latter case the driving motors are of the continuous-current type, and regenerative braking is not practicable (since the mercury-vapour rectifier is not reversible). The mercury-vapour rectifier is now being developed in large sizes, and although experimental work is still in progress, the successful application of large rectifiers (of 1000 kw. or more in a single unit) is expected to be an accomplished fact in the near future.

* Motors and control equipments for operating at 5000 volts have recently been developed (by the Westinghouse Co.) and put into service on the Michigan United Traction Co.'s lines. See *Electric Journal*, vol. 13, p. 445.

† This system has been designated "the split-phase system."

The application of rectified current to continuous-current motors, however, may necessitate slight modifications in the present construction of the motors.

In Table I are given data of a number of electric railways in this country and abroad. The extent of the practical application of the above systems of electrification can be seen from this table.

The **generation of electrical energy** and its distribution is a business in itself. In many cases it is desirable for the Railway Company to purchase power, since the Company is thereby relieved not only of the initial cost of the generating station and the capital charges thereon, but also of the management of a business organisation which is very different from its other organisations. In the United States of America the purchase of power for railway electrification from the large electric power supply companies is carried out on an extensive scale ; * but in this country, owing to the limited number of large power supply companies and their distance, in many cases, from the area of electrification, there are only two examples of the purchase of power for railway electrification—viz. the North-Eastern Railway (which purchases its power from the North-East Coast power supply companies) and the London Brighton, and South Coast Railway (which purchases its power from the London Electric Supply Corporation, Deptford).

As the subject of the generation of electrical energy is one of considerable magnitude at the present day, and has little bearing on the utilisation of the energy for traction purposes, we shall not consider the equipment of the generating station. The equipment of the sub-stations, however, is considered in detail, since, when power is purchased, the sub-stations would generally (although not necessarily) be under the control of the Railway Company.

NOTE.—The following papers contain much information on railway electrification under British conditions :

- “ The Electrification of Suburban Railways ” (F. W. Carter), *Proceedings of the Institution of Mechanical Engineers* (1910), p. 1073.
- “ The Cost of Electrically-propelled Suburban Trains ” (H. M. Hobart), *ibid.*, p. 1103.
- “ The Equipment and Working Results of the Mersey Railway under Steam and under Electric Traction ” (J. Shaw), *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 179, p. 19.
- “ Some Railway Conditions governing Electrification ” (Roger T. Smith), *Journal of the Institution of Electrical Engineers*, vol. 52, p. 293.
- “ Electrification of Railways as affected by Traffic Considerations ” (H. W. Firth), *ibid.*, p. 609.

* In this connection see the following papers in the *Transactions of the American Institute of Electrical Engineers* :

“ 2400-volt (continuous-current) Railway Electrification ” (H. M. Hobart), vol. 32, p. 1149 ; “ Trunk-line Electrification ” (C. P. Kahler), vol. 32, p. 1189 ; “ Mountain Railroad Electrification ” (A. H. Babcock), vol. 32, p. 1845 ; “ The Electrification of the Butte-Anaconda Railroad ” (J. B. Cox), vol. 33, p. 1369.

See also “ The Electrification of the Puget Sound Lines of the Chicago, Milwaukee, and St. Paul Railway,” *General Electric Review*, vol. 18, p. 5.

TABLE I.—DATA OF ELECTRIC RAILWAYS

Railway.	Mileage.		Class of Traffic.	System of Distribution.	Frequency.	Voltage of Distribution.	Method of Distributing Power to Trains.	System of Train Operation.	Motors.	
	Route Miles.	Equivalent Miles of Single Track.							Type.	Operating Voltage.
British—	North-Eastern	30	passenger freight	continuous current	..	550 1,500	conductor rails overhead conductors	motor-coach locomotive	series	550 750
	Lancashire and Yorkshire*	87½ 10	passenger	"	..	600 1,200	conductor rails overhead conductors	motor-coach	"	600 1,200
	Metropolitan District (London)	3½ 41	"	"	..	8,750 600	conductor rails overhead conductors	"	"	1,875 600
	Metropolitan (London)	30	"	"	..	600	"	motor-coach and locomotive	"	600
	London Electric Tube Railways	39	"	"	..	600	"	motor-coach	"	600
	Great Western (Suburban)	5	"	"	..	600	"	"	"	600
	London and South-Western	47	"	"	..	600	"	"	"	600
	London and North-Western	87½†	"	"	..	600	"	"	"	600
	Mersey	4½	"	"	..	600	"	"	"	600
	London, Brighton, and South Coast	26½	"	single-phase	25	6,600	overhead conductors	"	compensated repulsion compensated series	750 320
American—	Midland (Morecambe Branch)	9½	"	"	25	6,600	"	"	"	320
	New York Central	50	passenger (terminal)	continuous current	..	650	conductor rails	locomotive	series	650
	Pennsylvania (New York Section)	15	passenger (terminal)	"	..	650	"	"	"	650
	Pennsylvania (Philadelphia-Paoli Section)	20	passenger	single-phase	25	11,000	overhead conductors	motor-coach	series repulsion	..
	New York, New Haven, and Hartford (including branches)	112	passenger and freight	"	25	11,000	"	motor-coach and locomotive	compensated series	275
	Butte, Anaconda, and Pacific	27	"	continuous current	..	2,400	"	locomotive	series	1,200
	Chicago, Milwaukee, and St. Paul	440	"	"	..	3,000	"	"	"	1,500
	Great Northern (Cascade Tunnel)	4	freight	three-phase	25	6,600	"	"	polyphase induction	625
	Norfolk and Western	30	"	single-phase	25	11,000	"	"	"	725
	Italian State Railways	135	passenger and freight	three-phase	15 and 16½	8,000 & 3,300	"	"	"	3,000 & 3,300
	Simplon Tunnel	12½	passenger	"	16	8,000	"	"	"	8,000
	Lötschberg-Simplon (Bernese Alps)	46	"	single-phase	15	15,000	"	"	compensated series	420

* Including the Liverpool Overhead Railway. † The L. and N. W. R. electric trains also operate over 2½ (route) miles of track equipped by Metropolitan-District Railway.
; The electrification of an additional 150 miles of single track is in progress.

CHAPTER II

THE MECHANICS OF TRAIN MOVEMENT

I. PRELIMINARY STUDY OF SPEED-TIME CURVES

THE motion of a train or any vehicle is made up of periods of acceleration, of retardation, and, in some cases, of constant speed. Now, acceleration and retardation represent the rate of change of speed with respect to time: therefore, a curve which shows the speed of the train with respect to time will also supply information concerning the acceleration and retardation. For example, the acceleration or retardation at any instant can be obtained by determining the tangent of the angle of inclination of this curve (at the given instant) to the time axis—an upward slope (tangent positive) indicating acceleration, and a downward slope (tangent negative) indicating retardation. The acceleration, or retardation, obtained by this method will be given in terms of the units adopted for the axes of speed and time. If the former is represented in miles per hour and the latter in seconds, the acceleration or retardation will be expressed in miles per hour per second (abbreviated, ml.p.h.p.s.).*

Further, the distance travelled by the train during a given interval of time can be obtained by determining the area between the curve and the time axis corresponding to this interval.

It is apparent, therefore, that curves of the above type (which are called “speed-time” curves) are of considerable importance in connection with the movement of trains. But in electric traction these curves are of *fundamental importance*, since, if we are also provided with the characteristic curves of the driving motors, we can calculate the energy consumed by the train during the run. Moreover, with a knowledge of the resistances to motion, we are able to *estimate* the energy required to operate a train to a given schedule, as soon as the speed-time curve, corresponding to this schedule, has been determined.

It is necessary, therefore, to consider in detail the various portions of the speed-time curve, and to show how the curve corresponding to a given schedule may be obtained.

A speed-time curve, for a run between two stations, is usually made up of periods of—(1) acceleration; (2) constant speed, or “free running” (which may be zero for short distance runs); (3) coasting, *i.e.* running with power shut off, the retardation being due to the resistances to motion; and (4) retardation or braking.

* In this treatise we shall generally express acceleration in this manner, since speeds, in tramway and railway calculations, are usually expressed in miles per hour.

It is useful to remember that an acceleration of one mile per hour per second is equivalent to 1.47 feet per second per second.

With electric trains, equipped with series motors, the period of acceleration is made up of—(a) an initial period, during which the acceleration is practically constant, followed by (b) a period in which the acceleration gradually decreases until the maximum speed is reached.

The period of constant acceleration corresponds to the “notching” or starting period, during which the current input to the motors can be maintained practically constant (the value, of course, depending on the number of notches, the grading of the rheostats, and the rate at which the rheostats are cut out).

When full voltage is applied to the motors, the current and torque will decrease as the speed increases. Therefore the acceleration will gradually decrease until the torque is just sufficient to balance the resistances to motion. The shape of this portion of the speed-time curve will depend entirely on the shape of the speed-torque curve of the motor, and will be affected to some extent by variations in the line voltage and in the resistances to motion.

These two portions of the accelerating period are called respectively “rheostatic acceleration” or “acceleration while notching,” and “acceleration on the speed curve” or “speed-curve running.”

The duration of the free-running and coasting periods will depend on the nature of the service (that is, the distance between the stops and the average speed between the stations), and will be affected by the acceleration and retardation, as discussed below.

The classes of service into which passenger traffic can be divided are—(1) urban or city service, where the distance between stops is of the order of 0.5 mile; (2) suburban service, where the distance between the stops may average from 1.5 to 2 miles over a distance of from 15 to 20 miles from the city terminus; (3) main-line service, where the stops are infrequent.

Typical speed-time curves for electric trains operating on these services are given in Figs. 1, 2, 3.

In Fig. 1, which corresponds to city service, it is necessary to adopt relatively high values for the acceleration and retardation in order to obtain a moderately high average speed between the stations. The short distance between the stations does not permit of a free-running period, since it is desirable to include a short coasting period in order to obtain a reasonable energy consumption. This class of traffic requires a frequent service of trains.

In suburban service (Fig. 2) the longer distance between the stations permits of a free-running period and a longer coasting period than is possible with city service.

In this case also, relatively high values for the acceleration and retardation are required in order to render the service as attractive as possible. Moreover, at

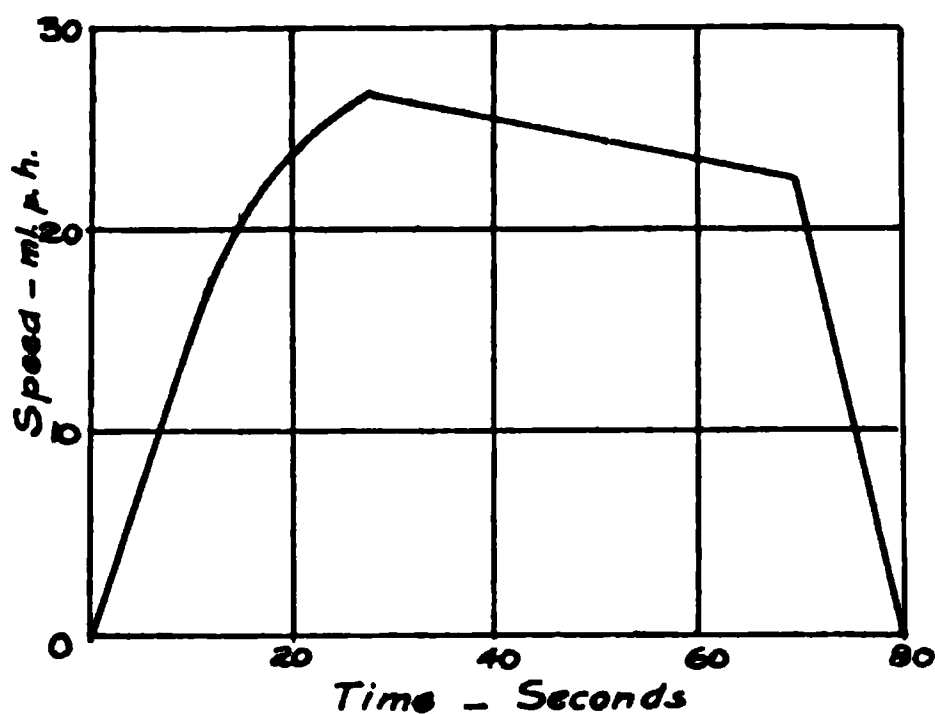


FIG. 1.—Speed-time Curve for City Service.

certain periods in the day, there will be a large traffic in one direction, which will require a frequent service of trains during these periods.

Main-line service (Fig. 3) is characterised by the long periods of

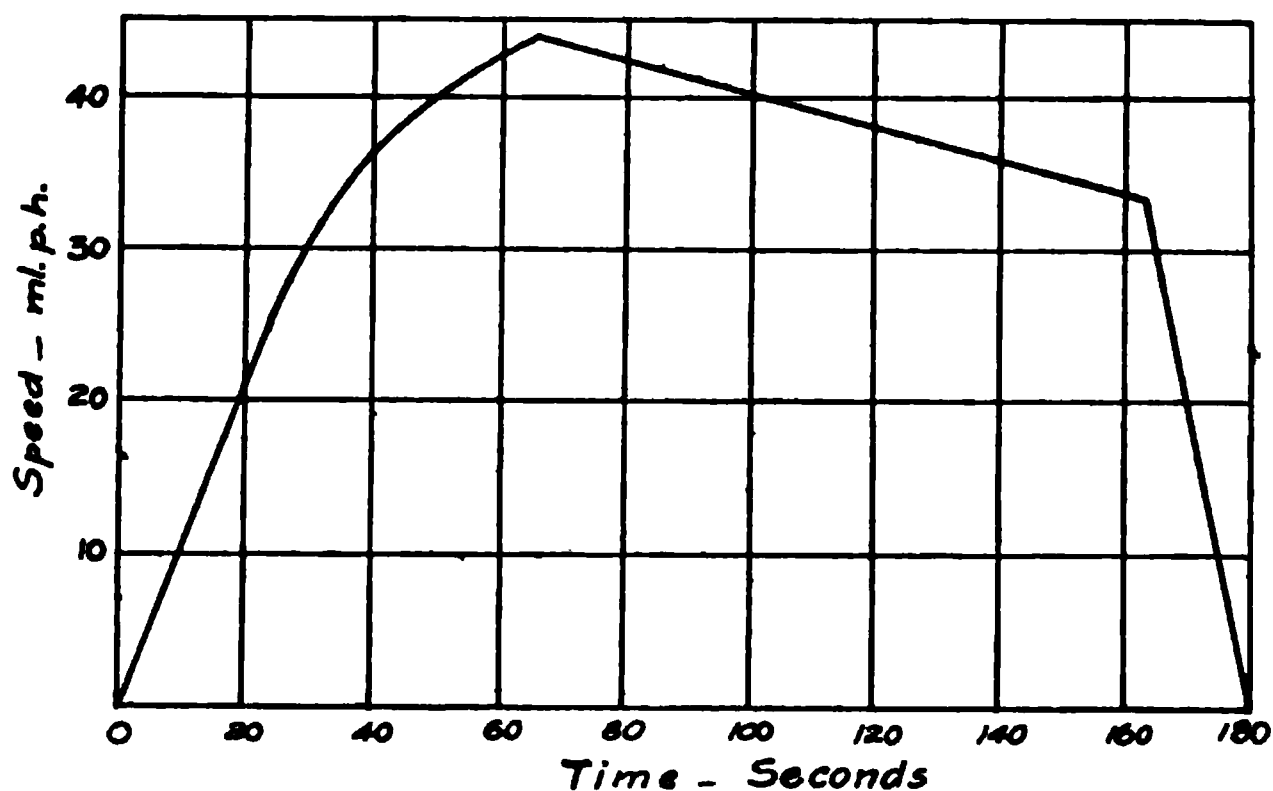


FIG. 2.—Speed-time Curve for Suburban Service.

free-running at high speeds, the accelerating period being relatively unimportant.

It is apparent, therefore, that the requirements for urban and main-line services are totally dissimilar, hence an equipment designed for main-line service will be totally unsuited for urban service, and vice versa. The full discussion of this point, however, must be deferred until later.

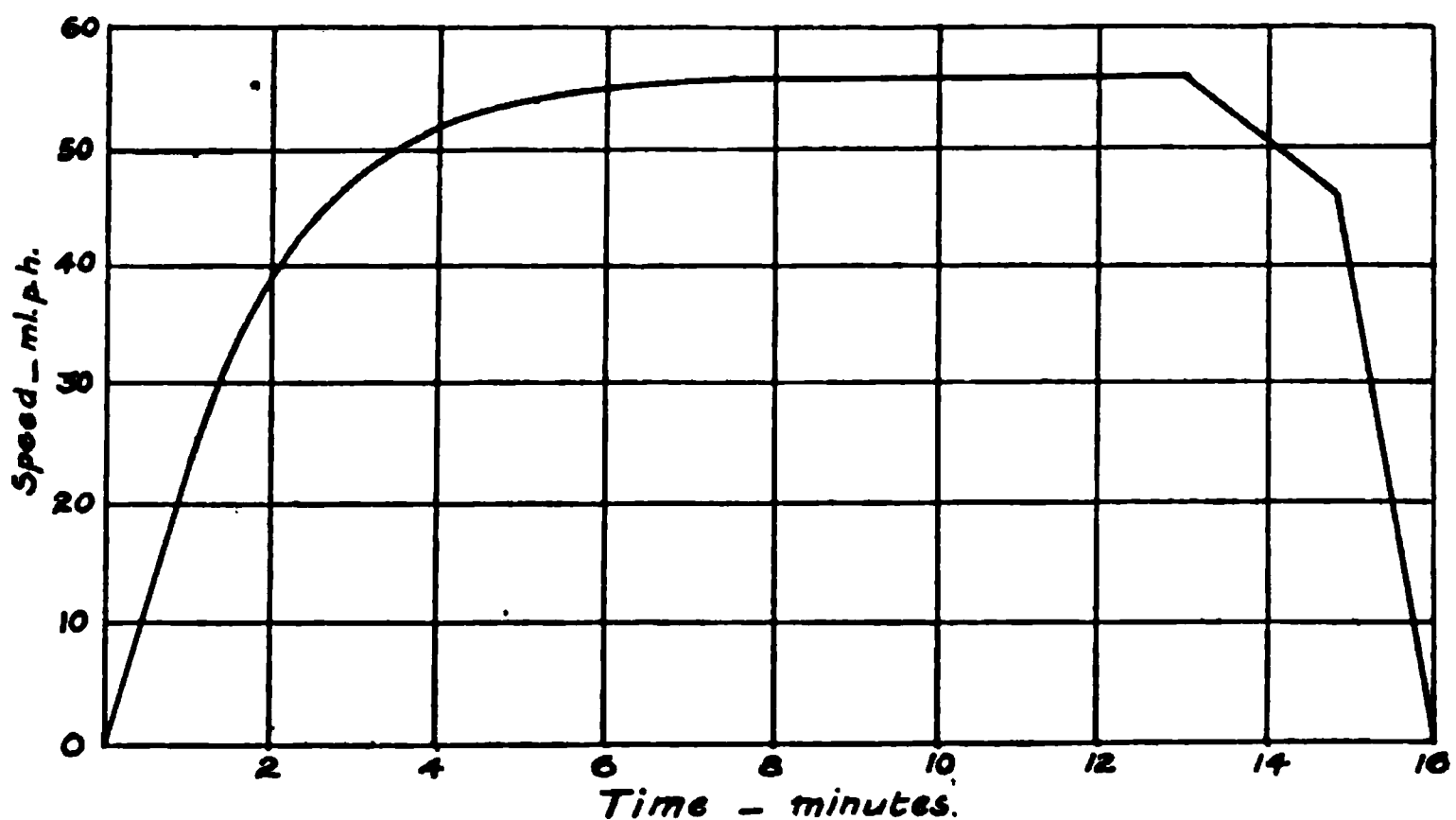


FIG. 3.—Speed-time Curve for Main-line Service.

The initial acceleration for electric trains is from 1.0 to 1.5 miles per hour per second. These values are from two to three times those obtained with the ordinary class of steam locomotive.

The limitations to the acceleration are—(1) the weight of the equipment; (2) the peak load on the sub-stations and power house; (3) the discomfort of the passengers; while, in addition, there are financial considerations, such as—(4) the cost of the rolling stock and equipment; (5) the maintenance charges on the equipment and rolling stock; (6) the cost of energy.

With the adoption of a high acceleration it becomes necessary to employ a high retardation, in order to obtain a reasonable energy consumption, since, for a given acceleration and average speed, the higher the retardation the longer will be the coasting period,* and, therefore, the shorter the time during which power is supplied to the motors. With modern types of quick-acting brakes, a retardation up to $3\frac{1}{2}$ miles per hour per second can be obtained. For urban and suburban services at high schedule speeds the retardation during braking is from 2.0 to 2.5 miles per hour per second.

Where comparative performances for a given service, at various schedule speeds, are required (for example, in preliminary calculations for time-tables, &c.), the actual speed-time curves of Figs. 1, 2, 3 are replaced by simplified speed-time curves, which do not involve a knowledge of the motor characteristic.

Thus, as far as the running of the distance between stops is concerned, Fig. 1 can be replaced by Fig. 4, in which the initial acceleration and the rate of braking are the same as in Fig. 1, and the area between the curve and time-axis is the same for each. The coasting and speed-curve running periods of Fig. 1 are included in the constant speed period of Fig. 4. This simplified speed-time curve will have a lower maximum speed than the actual speed-time curve which it replaces, although the average speed will be the same in each. Figs. 2 and 3 can be similarly modified.

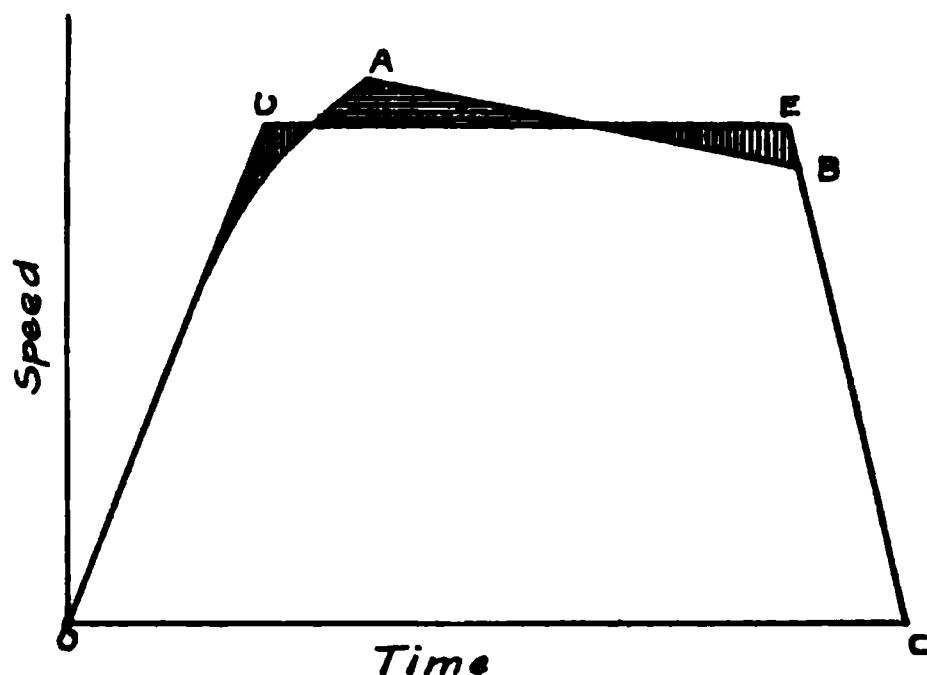


FIG. 4.—Method of Simplifying Speed-time Curve. Area OABC = area ODEC.

When the distance between stops, the average speed, the acceleration, and the retardation are known, the maximum speed can be calculated, and the simplified speed-time curve can be drawn.

Let α = acceleration, in miles per hour per second (ml.p.h.p.s.).

β = retardation, in the same units.

v = average speed, in miles per hour.

V_m = maximum speed, in miles per hour.

D = distance between stops, in miles.

T = running time, in seconds.

t_1 = time of acceleration, in seconds.

t_2 = time of free running, in seconds.

t_3 = time of braking, in seconds.

* With a given distance between stops, the running time and the area of the speed-time diagram must be constant.

Then
$$v = \frac{D}{T} \times 3600, \quad t_1 = \frac{V_m}{a}, \quad t_3 = \frac{V_m}{\beta}.$$

Now the area of the speed-time diagram is equal to the distance between the stops. Hence

$$\begin{aligned} D &= \frac{1}{3600} \left\{ \frac{1}{2} V_m t_1 + V_m t_2 + \frac{1}{2} V_m t_3 \right\} \\ &= \frac{1}{3600} \left\{ \frac{1}{2} V_m t_1 + V_m [T - (t_1 + t_3)] + \frac{1}{2} V_m t_3 \right\} \\ &= \frac{1}{3600} \left\{ -\frac{1}{2} V_m t_1 + V_m T - \frac{1}{2} V_m t_3 \right\}. \end{aligned}$$

Substituting for t_1 and t_3 , we have

$$D = \frac{1}{3600} \left\{ -\frac{V_m^2}{2a} + V_m T - \frac{V_m^2}{2\beta} \right\}$$

or
$$\frac{1}{7200} V_m^2 \left(\frac{1}{a} + \frac{1}{\beta} \right) - \frac{V_m T}{3600} + D = 0,$$

whence
$$V_m = \left(\frac{a\beta}{a+\beta} \right) T - \sqrt{\left(\frac{a\beta}{a+\beta} \right)^2 T^2 - 7200 D \left(\frac{a\beta}{a+\beta} \right)} \quad \dots \quad (1)$$

Now
$$\frac{1}{a} + \frac{1}{\beta} = \frac{7200}{V_m^2} \left(\frac{V_m T}{3600} - D \right)$$

and
$$\frac{T}{3600} = \frac{D}{v}.$$

Hence
$$\frac{1}{a} + \frac{1}{\beta} = \frac{7200 D}{V_m^2} \left(\frac{V_m}{v} - 1 \right)$$

whence
$$\frac{1}{a} = \frac{7200 D}{V_m^2} \left(\frac{V_m}{v} - 1 \right) - \frac{1}{\beta} \quad \dots \quad (2)$$

We shall now apply these equations to the calculation of speed-time curves to show the effect, on the schedule speed, of the acceleration, the distance between stops, the duration of stop, and the maximum speed.

Schedule speed is defined as:
$$\frac{\text{distance between stops}}{\text{time from start to start}},$$

while **average speed** means:
$$\frac{\text{distance between stops}}{\text{time from start to stop}}.$$

The effect of the duration of the stop on the schedule speed, for a given average speed, is shown in Table II, which emphasises the importance of short stops for urban service. For this class of service a stop of 15 to 20 seconds' duration is generally sufficient. The effect of increasing the stop (in Table II) from 10 to 20 seconds reduces the schedule speed by 10 per cent.; and if the stop is increased to 40 seconds, the schedule speed will be 16·4 per cent. less than that with a stop of 20 seconds. With longer distances between stations, the duration of the

stop can be increased without affecting the schedule speed to any great extent. Thus, comparing the 2 mile and 5 mile runs, the effect of increasing the duration of stop from 20 to 40 seconds reduces the schedule speeds by 5·4 per cent. and 2·4 per cent. respectively.

TABLE II

SCHEDULE SPEEDS CORRESPONDING TO AN AVERAGE SPEED OF 22 ML.P.H. FOR VARIOUS DISTANCES BETWEEN STOPS AND DURATION OF STOP.

Distance between stops :	0·5 mile	1·0 mile	2 miles	5 miles
Duration of Stop.	SCHEDULE SPEED.			
seconds.	ml.p.h.	ml.p.h.	ml.p.h.	ml.p.h.
10	19·6	20·8	21·3	21·7
20	17·7	19·6	20·7	21·4
30	16·1	18·6	20·1	21·2
40	14·8	17·7	19·6	20·9
50	13·7	16·9	19·1	20·7
60	12·7	16·1	18·6	20·5

Table III gives the **minimum acceleration** required to maintain various schedule speeds under various conditions. The rate of braking has been taken at 2·0 ml.p.h.p.s. in all cases, and the maximum speed from 20 per cent. to 40 per cent. above the average speed, depending on the distance between stops. This gives conditions which are similar to those encountered in practice, since, the longer the distance between stops, the lower will be the ratio between maximum and average speeds. The method by which the figures, in the last column of Table III, have been obtained may be illustrated by working through an example. Thus, consider that the run of $\frac{1}{2}$ mile between stops is to be made at a schedule speed of 20 ml.p.h., with a stop of 20 seconds, other conditions being as above. Then we have

$$\begin{aligned} \text{Schedule time} &= \frac{0\cdot5 \times 3600}{20} = 90 \text{ sec.} \\ \text{Running time} &= 90 - 20 = 70 \text{ sec.} \\ \text{Average speed} &= \frac{0\cdot5 \times 3600}{70} = 25\cdot7 \text{ ml.p.h.} \end{aligned}$$

The maximum speed is 40 per cent. greater than this (*i.e.* 36 ml.p.h.). Inserting this value in equation (2) we obtain

$$\frac{1}{a} = \frac{7200 \times 0\cdot5}{(36)^2} (1\cdot4 - 1) - \frac{1}{2} = 0\cdot61,$$

whence $a = 1\cdot64 \text{ ml.p.h.p.s.}$

TABLE III

MINIMUM ACCELERATION REQUIRED FOR VARIOUS SERVICES.
BRAKING RETARDATION : 2·0 ML.P.H.P.S.

Distance between Stops.	Duration of Stop.	Schedule Speed.	Schedule Time.	Running Time.	Average Speed.	Ratio :— Maximum Speed Average Speed	Maximum Speed.	Minimum Accelera- tion.
miles.	seconds.	ml.p.h.	seconds.	seconds.	ml.p.h.		ml.p.h.	ml.p.h.p.s.
0·5	10	15	120	110	16·36	1·4	22·9	0·45
		20	90	80	22·5		31·5	1·05
		25	72	62	29		40·6	2·68
	20	15	120	100	18	1·4	25·2	0·57
		20	90	70	25·7		36	1·64
		25	72	52	34·6		48·4	8·7
1·0	10	20	180	170	21·17	1·3	27·5	0·425
		25	144	134	26·85		34·9	0·79
		30	120	110	32·7		42·5	1·44
		35	102·8	92·8	38·8		50·5	2·9
	20	20	180	160	22·5	1·3	29·25	0·5
		25	144	124	29		37·7	0·98
		30	120	100	36		45·5	1·85
		35	102·8	82·8	43·5		56·6	5·7
2·0	10	20	360	350	20·57	1·2	24·7	0·237
		25	288	278	25·9		31·1	0·4
		30	240	230	31·3		37·6	0·65
		35	206	196	36·7		44	1·0
	20	20	360	340	21·08	1·2	25·3	0·25
		25	288	268	26·85		32·2	0·44
		30	240	220	32·7		39·3	0·73
		35	206	186	38·7		46·4	1·2
	30	20	360	330	21·8	1·2	26·2	0·27
		25	288	258	27·9		33·5	0·48
		30	240	210	34·3		41·2	0·83
		35	206	176	40·9		49·1	1·43

Table IV gives the **schedule speeds**, corresponding to various values of acceleration, for various conditions, the rate of braking and ratio of maximum to average speed being the same as in Table III.

The results of Tables II, III, and IV are plotted in Figs. 5, 6, and 7 (p. 16).

TABLE IV
 SCHEDULE SPEEDS CORRESPONDING TO VARIOUS SERVICES.

Distance between Stops.	Acceler- ation.	Braking Retard- ation.	Maxi- mum Speed.	Ratio :— Maximum Speed Average Speed	Average Speed.	Running Time.	Duration of Stop.	Schedule Time.	Schedule Speed.
miles.	ml.p. h.p.s.	ml.p. h.p.s.	ml.p.h.		ml.p.h.	seconds.	seconds.	seconds.	ml.p.h.
0.5	1.0	2.0	31.2	1.4	22.3	80.7	10	90.7	19.6
							20	100.7	17.8
	1.25		33.3		23.8	75.6	10	85.6	21
							20	95.6	18.8
	1.5		35.1		25.1	71.7	10	81.7	22
							20	91.7	19.6
	1.75		36.7		26.2	68.7	10	78.7	22.9
							20	88.7	20.3
	2.0		38		27.2	66.1	10	76.1	23.6
							20	86.1	20.9
1.0	0.75	2.0	34.3	1.3	26.4	136.5	10	146.5	24.6
							20	156.5	23
	1.0		38		29.25	123	10	133	27.1
							20	143	25.2
	1.25		40.8		31.4	114.6	10	124.6	28.9
							20	134.6	26.7
	1.5		43		33.1	108.8	10	118.8	30.8
							20	128.8	28
	2.0		46.5		35.8	100.5	10	110.5	32.6
							20	120.5	29.9
2.0	0.5	2.0	34	1.2	28.4	254	20	274	26.3
							30	284	25.4
	0.75		39.6		33	218	20	238	30.3
							30	248	29
	1.0		43.8		36.5	197	20	217	33.2
							30	227	31.7
	1.25		47.1		39.3	183.5	20	203.5	35.4
							30	213.5	33.7

NOTE.—The maximum speed is obtained from equation (2), thus :—

$$\left(\frac{1}{a} + \frac{1}{\beta}\right) = \frac{7200D}{V_m^2} \left(\frac{V_m}{v} - 1\right),$$

or

$$V_m = \sqrt{\frac{a\beta}{a + \beta} \left[7200D \left(\frac{V_m}{v} - 1\right) \right]},$$

the ratio $\frac{V_m}{v}$ being known.

A study of these tables and curves shows the necessity of a high acceleration, if a high schedule speed is desired, in urban and suburban service. It is evident that no steam locomotive could run a service at a schedule speed of 20 ml.p.h. with a stop every $\frac{1}{2}$ mile, even when the duration of the stop is only 10 seconds, but it is quite within the

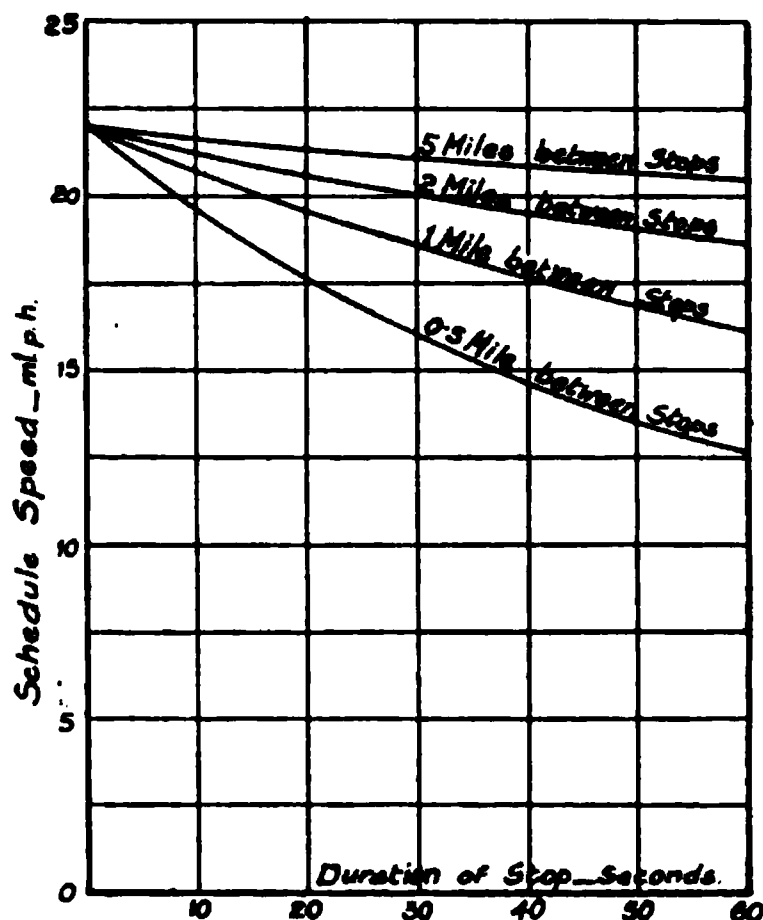


FIG. 5.—Influence of Duration of Stop and Length of Run on Schedule Speed.

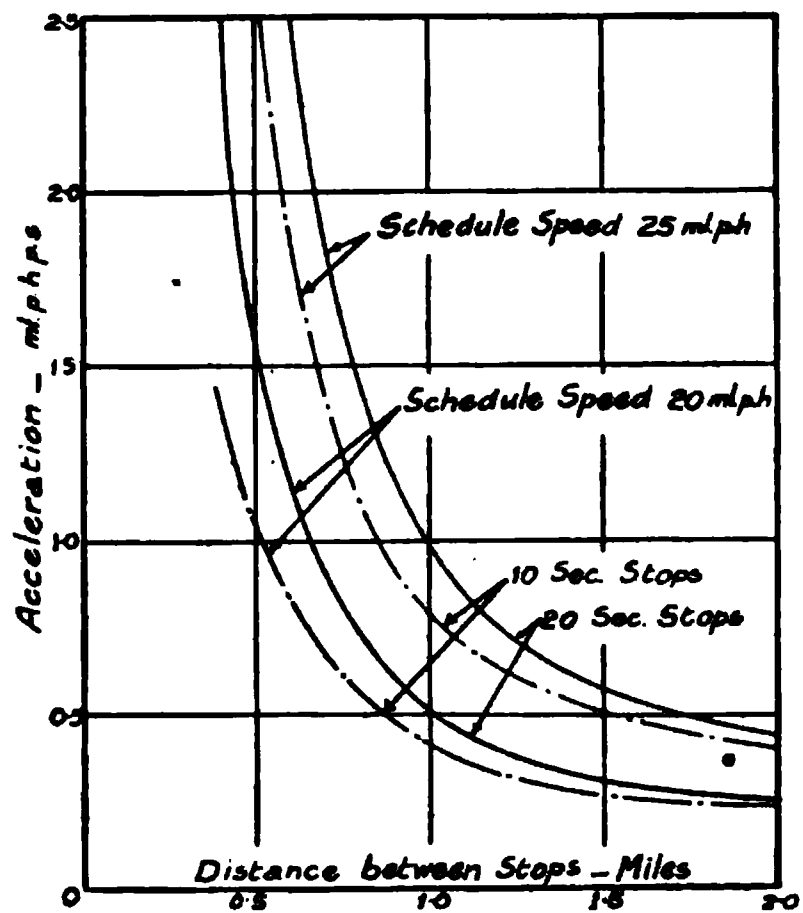


FIG. 6.—Minimum Acceleration to maintain given Schedule Speeds with various Distances between Stops.

range of electric traction to run this service with a stop of 20 seconds' duration.

When we consider longer distances (e.g. above 1 mile) between stops, the importance of a high acceleration is not so marked, and a steam

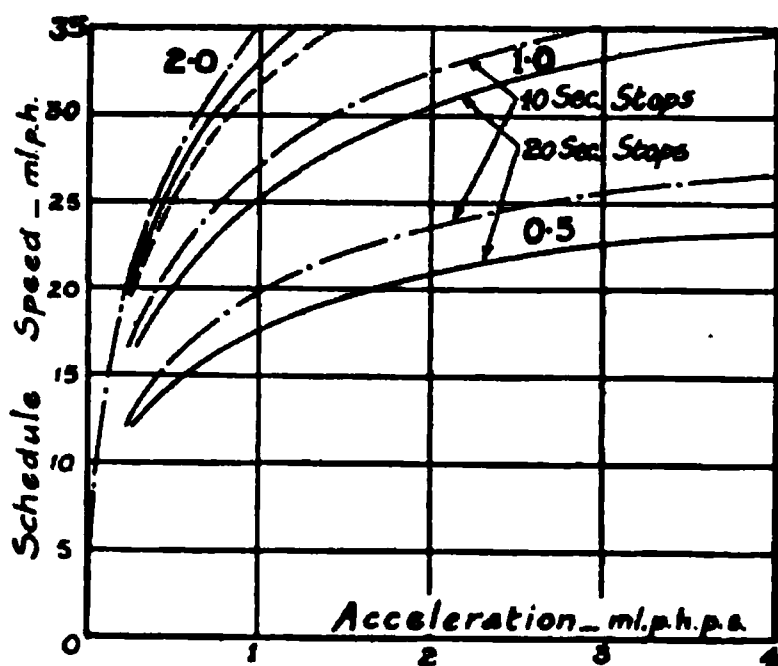


FIG. 7.—Schedule Speeds corresponding to runs of 0.5, 1.0, and 2.0 miles, with various Values of Acceleration.

locomotive would be quite capable of running a service at a schedule speed of over 25 ml.p.h. with a stop of 30 seconds' duration at stations 2 miles apart.

CHAPTER III

THE MECHANICS OF TRAIN MOVEMENT

II. PRELIMINARY INVESTIGATION OF ENERGY CONSUMPTION

WE have seen how the speed of a train can be represented during any interval of its motion, and it is now necessary to consider the manner in which the energy required can be estimated.

When electricity is applied to the operation of tramway and railway systems from a central power station, it is necessary to predetermine the amount of power required by the cars and trains, in order that the power-station equipment, sub-stations, feeders, &c., may be designed for economical working. The degree of accuracy to which this predetermination is possible will depend on the exactness of the available knowledge relating to the conditions of operation, such as schedule speed, distance between stops, frequency of service, weight of cars, &c. Thus, on railways, the schedule speeds are fixed by time-tables, and the operating conditions are known, but with street tramways the schedule speeds and the operating conditions are very variable. Nevertheless the average power required for a tramway system can be fairly well estimated. However, in this case, an exact estimation is not essential, as, apart from the variable conditions met with in street traffic, the maximum power taken by a tramcar is under 75 kw. On the other hand, a train may require as much as 2000 kw., and the necessity of an accurate determination of the power required is, therefore, obvious.

The total energy supplied to an electric train for propulsion may be expended in five ways, viz. : (1) in accelerating the train in a horizontal direction ; (2) in accelerating the revolving parts ; (3) in doing work against gravity, if the train is ascending a gradient ; (4) in overcoming the resistances to motion ; and (5) in supplying the losses in the motors and electrical equipment.

For short-distance runs at high schedule speeds, the energy required for the first and second items is a very large portion of the total energy supplied, while for long-distance runs at high speeds the energy required for item (4) will be considerably greater than that required for the remaining items.

The energy expended in accelerating the train is converted into kinetic energy, of which a portion is utilised during coasting, and the remaining portion is usually dissipated in the brake shoes.

The force (F), in pounds, necessary to produce an acceleration of a ml.p.h.p.s. on a body weighing W tons is given by

$$F = 102Wa^* \quad \dots \dots \dots (3)$$

In deriving this equation it is assumed that there are no rotating parts to be accelerated. However, the wheels, motor armatures, and other rotating parts on a train have to be accelerated in an angular direction as well as a linear one. The force required for the angular acceleration of the rotating parts can be obtained in the following manner:

Consider a wheel, of mass m and radius r , rotating about its axis. If a force f , in addition to that necessary to balance friction, is applied to the periphery of the wheel, the latter will be accelerated. If I is the moment of inertia of the wheel and a_a the angular acceleration, then

$$fr = Ia_a.$$

But $a_a = \frac{a}{r}$, where a is the linear acceleration of a point on the periphery of the wheel.

Also $I = mk^2$, where k is the radius of gyration.

Hence
$$f = ma\left(\frac{k}{r}\right)^2.$$

Adopting the same units as above, let

W_1 = weight of wheel in tons,

r_1 = radius of the tread in feet,

k_1 = radius of gyration in feet,

a = acceleration of train in ml.p.h.p.s.,

F_1 = the force, in lb., necessary for the angular acceleration of wheel,

then
$$F_1 = 102W_1a\left(\frac{k_1}{r_1}\right)^2 \quad \dots \dots \dots (4)$$

Now consider an armature driven through gearing from the axle of this wheel. Then, for an acceleration of a at the tread of the wheel, the angular acceleration of the armature will be $\frac{a}{r_1} \gamma$, where γ is the gear ratio. Hence, if F_2 is the force (in lb.), acting at the tread of the wheel,† to produce the angular acceleration of the armature, then

$$F_2 = 102W_2a\left(\frac{k_2}{r_1}\gamma\right)^2 = 102W_2a\gamma^2\left(\frac{k_2}{r_2}\right)^2\left(\frac{r_2}{r_1}\right)^2 \quad \dots \dots \dots (5)$$

where W_2 = weight of armature in tons,

k_2 = radius of gyration of armature in feet,

r_2 = radius of armature in feet.

The forces for the angular acceleration of the gear wheel and axle may be similarly obtained.

If n = number of axles on a train made up of motor and trail coaches, and n_1 = the number of motors, then the total force F_a (lb.), acting at the tread of the driving wheels, required for the acceleration of the train on level track, will be

$$F_a = F + 2nF_1 + n_1F_2 + n_1F_3,$$

* $F(\text{lb.}) = \frac{W(\text{tons})}{g} \times 2240 \times 1.47a = 102Wa$, taking $g = 32.2$.

† It is necessary to consider this force acting at the tread of the wheel, as the characteristics of the motor are calculated for the output at this point.

where F_s is the force for the angular acceleration of each gear wheel, the axles being neglected. Hence

$$\begin{aligned} F_a &= 102W\alpha + 102W_1\alpha \cdot 2n\left(\frac{k_1}{r_1}\right)^2 + 102W_2\alpha n_1\gamma^2\left(\frac{k_2}{r_2}\right)^2\left(\frac{r_2}{r_1}\right)^2 + 102W_3\alpha n_1\left(\frac{k_3}{r_1}\right)^2 \\ &= 102\alpha\left\{W + 2nW_1\left(\frac{k_1}{r_1}\right)^2 + n_1W_2\gamma^2\left(\frac{k_2}{r_2}\right)^2\left(\frac{r_2}{r_1}\right)^2 + n_1W_3\left(\frac{k_3}{r_1}\right)^2\right\} \\ &= 102\alpha W_e \end{aligned} \quad (6)$$

where W_e is called the "effective" or "accelerating" weight of the train.

The amount by which W_e exceeds the dead weight of the train varies from 8 per cent. to 15 per cent. of the latter, the actual value depending on the number of wheels and motors, type of motor, &c.

In order to calculate the effective weight of a train, it is necessary to know the radius of gyration of each rotating part. The radius of gyration of a cylinder is $0.707 \times$ external radius; an average value for a steel-tired railway wheel is $0.77 \times$ radius of tread; * while, for the armature of a continuous-current or alternating-current commutator motor, the value of $0.7 \times$ external radius of armature core is approximately correct.† The radius of gyration of a gear wheel will depend on the design of the wheel, but, for the class of gear wheels used on motor-coach trains, the value of $0.8 \times$ radius of pitch circle will be sufficiently accurate.

Hence, inserting these values in the above equation, we have

$$\begin{aligned} W_e &= W + 2nW_1(0.77)^2 + n_1W_2\gamma^2(0.7)^2\left(\frac{r_2}{r_1}\right)^2 + n_1W_3(0.8)^2\left(\frac{r_3}{r_1}\right)^2 \\ &= W + 1.2nW_1 + 0.49n_1W_2\gamma^2\left(\frac{r_2}{r_1}\right)^2 + 0.64n_1W_3\left(\frac{r_3}{r_1}\right)^2 \end{aligned} \quad (7)$$

Example.—The electric trains on the South London section of the London, Brighton, and South Coast Railway are composed of two motor-coaches and two trailers. Each coach is mounted on two 4-wheel bogie trucks, and each axle of a motor-coach carries a single-phase motor of 115 H.P., which drives the axle through gearing having a gear ratio of 4.24 : 1. Each motor-coach (without passengers) weighs 54 tons, and each trailer coach weighs 24.25 tons. All wheels are $43\frac{1}{2}$ in. in diameter, and weigh 1010 lb. each. The motor armatures weigh 1850 lb. each, and have a diameter of approximately 20 in. The gear wheels have a pitch circle diameter of approximately $29\frac{1}{4}$ in., and weigh 300 lb. each.

The train will, therefore, have 16 axles and 8 motors. The dead weight of train is 156.5 tons.

Hence the effective weight will be

$$\begin{aligned} W_e &= 156.5 + \left\{\frac{1.2 \times 16 \times 1010}{2240}\right\} + \left\{0.49 \times 8 \times \frac{1850}{2240} \times (4.24)^2 \times \left(\frac{20}{43.5}\right)^2\right\} \\ &\quad + \left\{0.64 \times 8 \times \frac{300}{2240} \times \left(\frac{29.25}{43.5}\right)^2\right\} \\ &= 156.5 + 8.65 + 12.6 + 0.3 \\ &= 178 \text{ tons, or } 13.6 \text{ per cent. greater than the dead weight of the} \end{aligned}$$

* *Journal of the Institution of Electrical Engineers*, vol. 50, p. 436.

† *Ibid.*, p. 437.

train. It will be observed that only a very small error would have been introduced if the gear wheels had been neglected.

The **work done against gravity** when a train is ascending a gradient is equal to:—weight of train \times vertical distance through which it is elevated. The additional force (F_g , lb.) at the driving wheels to accelerate a train up a gradient is given by

$$F_g = 22.4WG^* \quad \dots \dots \dots (8)$$

(or 22.4 lb. per ton per 1 per cent. gradient), G representing the percentage gradient and W the weight of the train in tons.

The remaining item which must be known before the dynamical performance of train can be obtained is the resistance to motion, called "**train resistance**" or "train friction." This is made up of several variable components, of which none can be calculated from first principles. Our present knowledge of train resistance has been obtained from the experience of several investigators, who have proposed empirical formulæ, based on experimental results. Train resistance, in detail, is considered later, but for present purposes it may be pointed out that the specific train resistance of a motor-coach train is higher than that of the same number of coaches hauled by a locomotive. For locomotive-hauled trains, Aspinall's formula

$$\left[r = 2.5 + \frac{V^2}{50.8 + 0.0278L} \right] \text{ where } r = \text{specific train resistance in lb. per ton of train weight,}$$

$$L = \text{length of train in feet,}$$

$$V = \text{speed in miles per hour} \dagger$$

is usually considered as standard in this country. For motor-coach trains the following formula (38) is proposed: ‡

$$r = 4.1 + 0.055V + \frac{AV^2}{W} (0.0028k + 0.0000122nL),$$

where r = specific train resistance in lb. per ton of train weight,

W = weight of train in tons,

V = speed in miles per hour,

n = number of coaches,

A = cross-sectional area (in sq. ft.) at right angles to motion,

L = length of each coach in feet, and

k = a coefficient to include the effect due to the shape of the ends of the coaches.

These formulæ refer to train resistance at constant speed. When the speed is changing rapidly, the train resistance is greater than that at constant speed, and therefore, during the initial period of acceleration, we cannot apply these formulæ for the train resistance. Moreover, a relatively large variation in the train resistance, during this period, will have little effect on the dynamical performance of the train, since, in urban service, practically 95 per cent. of the total energy output

* The force acting down the gradient is $2240W \sin \theta$ (lb.), where θ is the angle of the gradient from the horizontal. When the gradient is expressed in the usual manner, this expression reduces to the above form.

† See paper on "Train Resistance" by Mr. J. A. F. Aspinall, *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 147, p. 155.

‡ See Chapter XVIII.

from the driving axles will be expended in acceleration. We are, therefore, justified in assuming an average value for the train resistance during the initial accelerating period, and, in practice, this is usually taken at from 7 to 10 lb. per ton weight of train. During speed-curve running (when the acceleration is gradually decreasing), and free running (i.e. constant speed), the train resistance should be obtained from the formulæ.

If r is the specific train resistance in lb. per ton weight of train, and W is the weight of the train in tons, the total train resistance will be $W \times r$ lb. When the train is running at uniform speed on level track, the total force or tractive effort at the driving wheels will be equal to the train resistance. The total power (P) at the driving axles will be:

$$\begin{aligned} P &= \frac{rWV \times 5280}{60 \times 33000} \text{ (H.P.)} \\ &= 0.00267rWV \text{ (H.P.)} \\ &= 0.00267 \times \frac{746}{1000} rWV \text{ (kw.)} \\ &= 0.002rWV \text{ (kw.)} \end{aligned} \quad (9)$$

where V is the speed of the train in miles per hour.

During the initial period of uniform acceleration, the total average output from the driving axles will be $P' = 0.002V'(102W_a + r'W)$ kw., where r' is the assumed value of the specific train resistance, and V' is the average speed during this period. For the period of speed-curve running, where the acceleration is variable, the output from the driving axles, at any instant, will be

$$P_1 = 0.002V_1(102W_a + r_1W) \text{ kw.},$$

where V_1 and a_1 are the instantaneous speed and acceleration, and r_1 is the train resistance at speed V_1 .

If the duration of the accelerating and free-running periods is known, then, by multiplying the above expressions for the power by the corresponding times, the energy output from the driving axles will be obtained. This will represent the energy required for dynamical purposes, which is entirely independent of the system of propulsion, except in so far as the latter affects W and W_a . The energy input to the motors will depend on the efficiency of the electrical equipment and the method of speed control.

The energy input to the motors is called the "**energy consumption**" of the train, since it is the energy used for propulsive purposes. The total energy taken from the conductor rails or overhead line will be greater than this by the amount required for lighting, heating, control and brake apparatus.

The energy consumption can be expressed in "kilowatt-hours per train mile," that is,

$$\frac{\text{energy consumption of train in kilowatt-hours}}{\text{length of run in miles}}$$

or in "watt-hours per ton mile," that is,

$$\frac{\text{energy consumption of train in watt-hours}}{\text{length of run in miles} \times \text{weight of train in tons}}$$

the latter being known as the **specific energy consumption**.

The **specific energy consumption** of trains operating at a given schedule speed is influenced by (1) the distance between stops, (2) the

acceleration, (3) the retardation, (4) the maximum speed, (5) the type of train and equipment, (6) the configuration of the track.

Generally, for a given run at a given schedule speed, the specific energy consumption will be lower the higher the acceleration and retardation, since by these means a longer coasting period can be obtained. However, due consideration must be given to the weight of the equipment, and the effect of this on the energy consumption of the train. For runs of short distances, a low specific energy consumption will generally indicate a low total energy consumption, but for longer distances it does not follow that a similar relation holds, since, in the latter case, the work done against train resistance is a considerable percentage of the total energy output from the axles. Table V shows that, in the case of long-distance runs, the effect of increased acceleration, in reducing the specific energy consumption, is altogether counteracted by the increased weight of the train leading to a greater total energy consumption.

Table V has been calculated for motor-coach trains weighing 200 and 225 tons operating at various schedules. The 200-ton train is considered to operate with an acceleration of 0.5 ml.p.h.p.s., while for the 225-ton train an acceleration of 1.0 ml.p.h.p.s. has been assumed. The braking retardation is 1.5 ml.p.h.p.s. in each case. The effective weight for the 200-ton train has been assumed at 216 tons, and at 247 tons for the 225-ton train. The energy output given in the table has been calculated (see below) on the basis of a simplified speed-time curve, consisting of periods of constant acceleration, constant speed, and constant retardation. The large percentage of energy wasted in the brakes for the short-distance runs should be noted.

In cases where the simplified speed-time curve can be applied, such as in *comparative* calculations similar to the above, the energy output from the driving wheels can readily be obtained from the following equations:

(1) **Energy required for acceleration** $= \frac{0.0283 V^2 \zeta}{D}$ * watt-hours per ton-mile, where V is the speed (in miles per hour) at the end of accelerating period, D is the distance between stops in miles, and ζ is the ratio of the effective weight to the dead weight (i.e. $\frac{W_e}{W}$). (10)

(2) **Work done against train resistance** $= 2 \frac{D'}{D}$ watt-hours per ton-mile † for each lb. per ton of train resistance, D' being the distance

* A body, having an effective weight of W_e tons, moving with a velocity of V miles per hour, possesses kinetic energy

$$= W \times 2240 \times \frac{V^2}{2g} \left(\frac{5280}{3600} \right) \times \frac{746}{550 \times 3600} \text{ watt-hours,}$$

$$= \frac{0.0283 V^2 W_e}{DW} = \frac{0.0283 V^2 \zeta}{D} \text{ watt-hours per ton-mile.}$$

† If W = weight of train in tons, r = specific train resistance in lb. per ton, the work done against train resistance over a distance D' miles will be: $5280 D' W r$ ft. lb. Converting this into watt-hours, we obtain $W r D' \left(\frac{5280 \times 746}{550 \times 3600} \right) = 1.99 W r D'$ watt-hours, which reduces to $1.99 r \frac{D'}{D}$ watt-hours per ton-mile for the whole run, or approximately $2 \frac{D'}{D}$ watt-hours per ton-mile for each lb. per ton of train resistance.

TABLE V
APPROXIMATE ENERGY CONSUMPTION OF TRAINS OPERATING ON VARIOUS SERVICES.
BRAKING RETARDATION 1.5 ML.P.H.P.S.

Distance between Stops.	Average Speed. ml.p.h.	Running Time. seconds.	Acceler- ation. ml.p.h.p.s.	Maximum Speed. ml.p.h.	Distance Travelled.		Specific Train Resistance.*		Weight Of Train. tons.	Energy Expended.		Specific Energy Consump- tion.	Energy Consump- tion of Train. kwh. per train mile.	Energy Dissipated in Brakes as Percentage of Total Energy Utilised.
					During Accelera- tion.	During Free- running.	For Ac- celerating Period.	For Free- running Period.		In Accelera- tion.	Against Train Resistance.			
0.75	20	135	{ 1.0 0.5	23.4 27.5	ml. 0.076 0.21	ml. 0.62 0.47	lb. per ton. 8 8.3	lb. per ton. 8 8.9	225 200	wh. per ton mile. 22.7 30.8	wh. per ton mile. 15 16.1	37.7 46.9	8.48 9.38	60 65.6
5	35	486	{ 1.0 0.5	40 42	0.22 0.48	4.66 4.39	10 10.5	12.5 13	225 200	9.9 10.8	24.2 24.8	34.1 35.6	7.68 7.12	29 30.3
30	50	2160	{ 1.0 0.5	51 51.7	0.45 0.74	29.4 29.05	13 13.2	16.4 16.7	225 200	2.7 2.72	32.55 34	35.25 36.7	7.94 7.34	7.65 7.4

* Assumed.

(in miles) over which work is done, and D the distance (in miles) between stops (11)

We shall now show how these equations have been applied to the calculation of Table V. Thus, considering the first run of $\frac{3}{4}$ mile between stops, the average speed is 20 ml.p.h., and consequently the running time is

$$\left(\frac{0.75 \times 3600}{20} =\right) 135 \text{ sec.}$$

The acceleration is 1.0 ml.p.h.p.s., and the retardation is 1.5 ml.p.h.p.s.

Inserting these values in equation (1) we obtain the maximum speed as 23.4 ml.p.h.

The time of acceleration is $\left(\frac{23.4}{1.0} =\right) 23.4$ sec., the time of braking is $\left(\frac{23.4}{1.5} =\right) 15.6$ sec., and the time of free running is 96 sec. The distance traversed during acceleration is $\left(\frac{23.4}{2} \times \frac{23.4}{3600} =\right) 0.076$ ml., and that during free running is $\left(23.4 \times \frac{96}{3600} =\right) 0.624$ ml.

Assuming the specific train resistance during acceleration and free running at 8 lb. per ton, we have : Energy used against train resistance

$$= 2 \times 8 \times \frac{(0.624 + 0.076)}{0.75} = 15 \text{ watt-hours per ton-mile.}$$

The energy used in acceleration

$$= \frac{0.0283 \times (23.4)^2 \times 247}{0.75 \times 225} = 22.7 \text{ watt-hours per ton-mile.}$$

The specific energy consumption (on the assumption of no losses in the train equipment) is $15 + 22.7 = 37.7$ watt-hours per ton-mile, and the

total energy consumption is $\frac{225 \times 37.7}{1000} = 8.48$ kw. hours per train-mile.

As an **example** of the application of the above methods we will consider the following problem :

A train weighing 150 tons (gross weight) runs to the following schedule : Distance between stops, 1.25 miles ; duration of stop, 30 seconds ; schedule speed, 20 ml.p.h.

There is a uniform "up" gradient of 1 in 150 the whole way.

Calculate the H.P. required from the motors and the energy demand from the generating station per ton-mile, assuming suitable figures where necessary. (C. & G., Grade III, Pt. III, 1915.)

The following data are assumed :

Acceleration (on level track) = 1.0 ml.p.h.p.s.

Braking retardation (on level track) = 2.0 ml.p.h.p.s.

Effective weight of train (considered as 8 per cent. greater than the dead weight)

= 162 tons.

Train resistance

= 10 lb. per ton.

The acceleration (or retardation) due to the grade is obtained by a combination of equations (8) and (6). Thus, if α , represents this acceleration (or retardation), then

$$\alpha = \frac{22.4WG}{102W_s} = \frac{22.4 \times 0.66}{102 \times 1.08} = 0.135 \text{ ml.p.h.p.s.}$$

Hence the *actual values* of the acceleration and retardation will be :

$$\text{Acceleration} = 1.0 - 0.135 = 0.865 \text{ ml.p.h.p.s.}$$

$$\text{Retardation during braking} = 2.0 + 0.135 = 2.135 \text{ ml.p.h.p.s.}$$

The running time is $\left[\left(\frac{1.25 \times 3600}{20} - 30 \right) = \right] 195 \text{ second}$, and the

average speed is $\left(\frac{1.25 \times 3600}{195} = \right) 23.1 \text{ ml.p.h.}$

We are now able to obtain the maximum speed by the application of equation (1) on the assumption of a *simplified speed-time curve* (Fig. 4).

$$\begin{aligned} \text{Thus } V_m &= \left(\frac{0.865 \times 2.135}{0.865 + 2.135} \right) \\ &195 - \sqrt{\left[\left(\frac{0.865 \times 2.135}{0.865 + 2.135} \right) 195 \right]^2 - 7200 \times 1.25 \left(\frac{0.865 \times 2.135}{0.865 + 2.135} \right)} \\ &= 24.8 \text{ ml.p.h.} \end{aligned}$$

We next determine the duration of the accelerating and free-running periods, and also the distances traversed during these periods. For convenience these calculations are arranged in tabular form :

$$\text{Duration of accelerating period } \left(t_1 = \frac{V_m}{a} \right) \quad . \quad . \quad . \quad 28.7 \text{ sec.}$$

$$\text{Duration of braking period } \left(t_3 = \frac{V_m}{\beta} \right) \quad . \quad . \quad . \quad 11.6 \text{ sec.}$$

$$\text{Duration of free running period } (t_2 = T - (t_1 + t_3)) \quad . \quad . \quad 154.7 \text{ sec.}$$

$$\text{Distance covered during acceleration } \left(D_1 = \frac{V_m}{2} \times \frac{t_1}{3600} \right) \quad . \quad 0.099 \text{ ml.}$$

$$\text{Distance covered during free running } \left(D_2 = V_m \frac{t_2}{3600} \right) \quad . \quad 1.066 \text{ ml.}$$

$$\begin{aligned} \text{Total distance covered during acceleration and free run-} \\ \text{ning } (D = D_1 + D_2) \quad . \quad . \quad . \quad 1.165 \text{ ml.} \end{aligned}$$

Therefore the energy used against train resistance (obtained by the application of equation (11)) is

$$\left(2 \times 10 \times \frac{1.165}{1.25} = \right) 18.65 \text{ watt-hours per ton-mile,}$$

while the work done against gravity is

$$\left(2 \times (22.4 \times 0.66) \times \frac{1.165}{1.25} = \right) 27.85 \text{ watt-hours per ton-mile.}$$

[NOTE.—The “resistance” due to gravity = 22.4G lb. per ton.]

The energy used in acceleration (obtained by the application of equation (10)) is

$$\left(\frac{0.0283 \times (24.8)^2 \times 1.08}{1.25} = \right) 15 \text{ watt-hours per ton-mile.}$$

Hence the energy demand from the generating station

$$= 18.65 + 27.85 + 15 = 61.5 \text{ watt-hours per ton-mile.}$$

The maximum output from the motors will occur at the end of the accelerating period, and will be equal to

$$\begin{aligned} [0.00267 \times 24.8(102 \times 162 \times 0.865 + 10 \times 150 + 0.66 \times 22.4 \times 150) =] \\ 1195 \text{ H.P.} \end{aligned}$$

[NOTE.—Apply the equations on p. 21.]

CHAPTER IV

CONTINUOUS-CURRENT TRACTION MOTORS

IN the last chapter we have shown that the tractive effort required for the acceleration of a train is, generally, considerably greater than that for free running, while additional tractive effort is required when negotiating up-gradients. With electric traction the tractive effort is supplied from the motors in the form of torque at the armature shaft, and, in a given case, the tractive effort will always bear a constant relation to the torque exerted by the motor, so that it is now necessary to consider the relations between the speed, torque, and current in continuous-current motors.

Now the gross torque exerted by the armature of any continuous-current motor is given by the equation

$$M = \frac{p}{c} \Phi I z \times \frac{1}{852} \quad \dots \dots \dots (12)$$

or
$$M = \frac{p \Phi I T}{426} \quad \dots \dots \dots (12a)$$

where M is the gross torque (in lb.-ft.), p the number of poles, c the number of circuits in the armature winding, z the number of conductors on the armature, T the number of turns in series between the brushes, I the total armature current (in amperes), Φ the flux per pole (in megalines). For a given type of armature winding and a given number of poles (i.e. a fixed value for the ratio p/c), the torque is proportional to the product of *flux and ampere conductors on the armature*, or, for a given motor, the torque is proportional to the product of *flux and armature current*.

Hence, in a shunt motor, the relation between the torque and the armature current can be represented by a straight line, but in compound and series motors the relation between these quantities cannot be expressed with such simplicity, on account of the variation of the flux with the armature current. In Fig. 8 are given comparative torque-current curves for ideal shunt, series, and compound motors in which we have assumed the armature windings and magnetic circuits to be identical, and have neglected the effects of armature reaction. From these curves we obtain the "specific torque" curves in Fig. 9, which provide us with a better comparison of the torque characteristics than the curves of Fig. 8.* The curves of Fig. 8 show clearly that, when a large torque

* Incidentally the curves in Fig. 9 represent the variation of the flux with armature current, since $\frac{M}{I} = \left(\frac{pT}{426} \right) \Phi$.

is required, the series motor will be able to perform this operation with a lower current consumption than the shunt motor.

Let us now consider the manner in which the speeds of the above

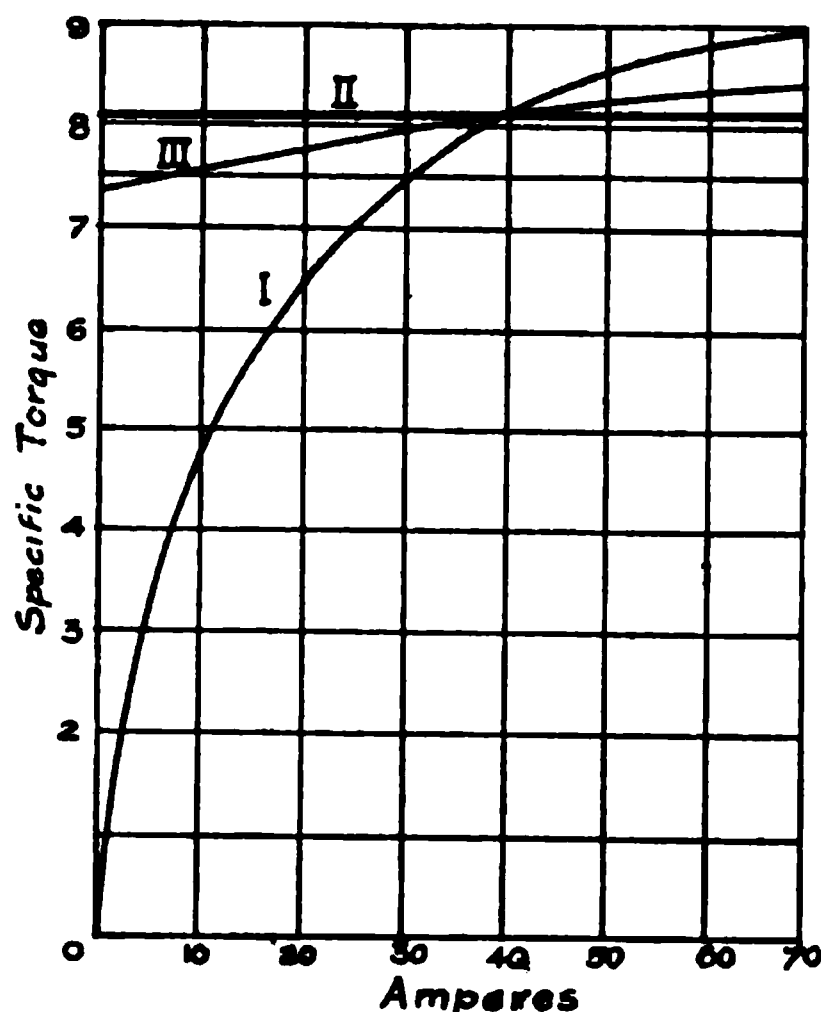
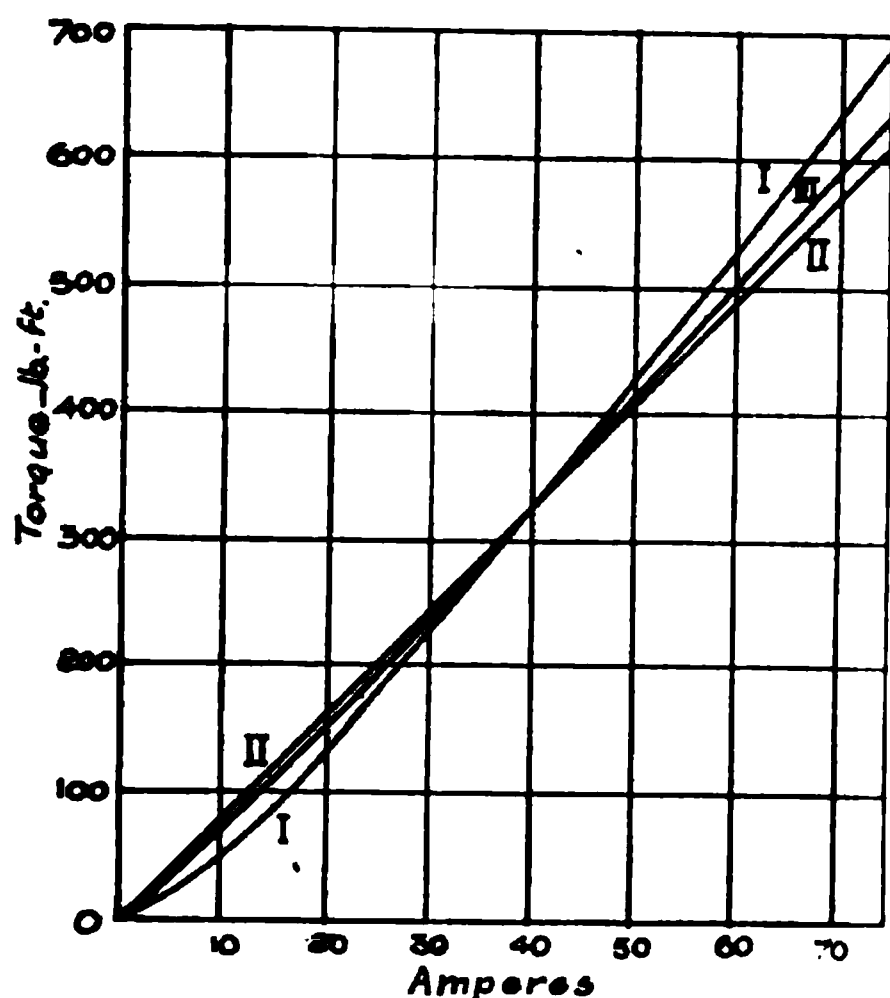


FIG. 8.—Comparative Torque Curves for Series (I), Shunt (II), and Compound (III) Motors.

FIG. 9.—Comparative Specific Torque (ft.-lb. per ampere) Curves for Series (I), Shunt (II), and Compound (III) Motors.

motors are affected by variations in the torque. The equation for the speed of a continuous-current motor is

$$n = \frac{3000(E - e)}{pT\Phi} \quad \dots \dots \dots (13)$$

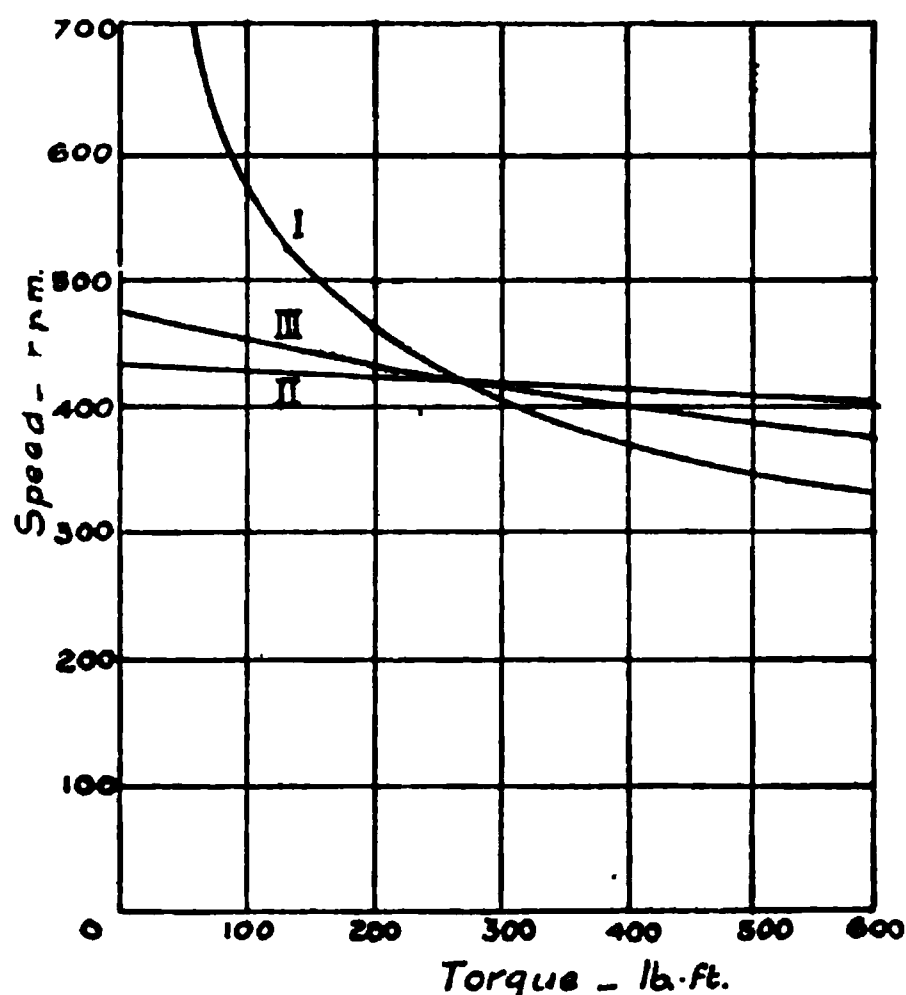
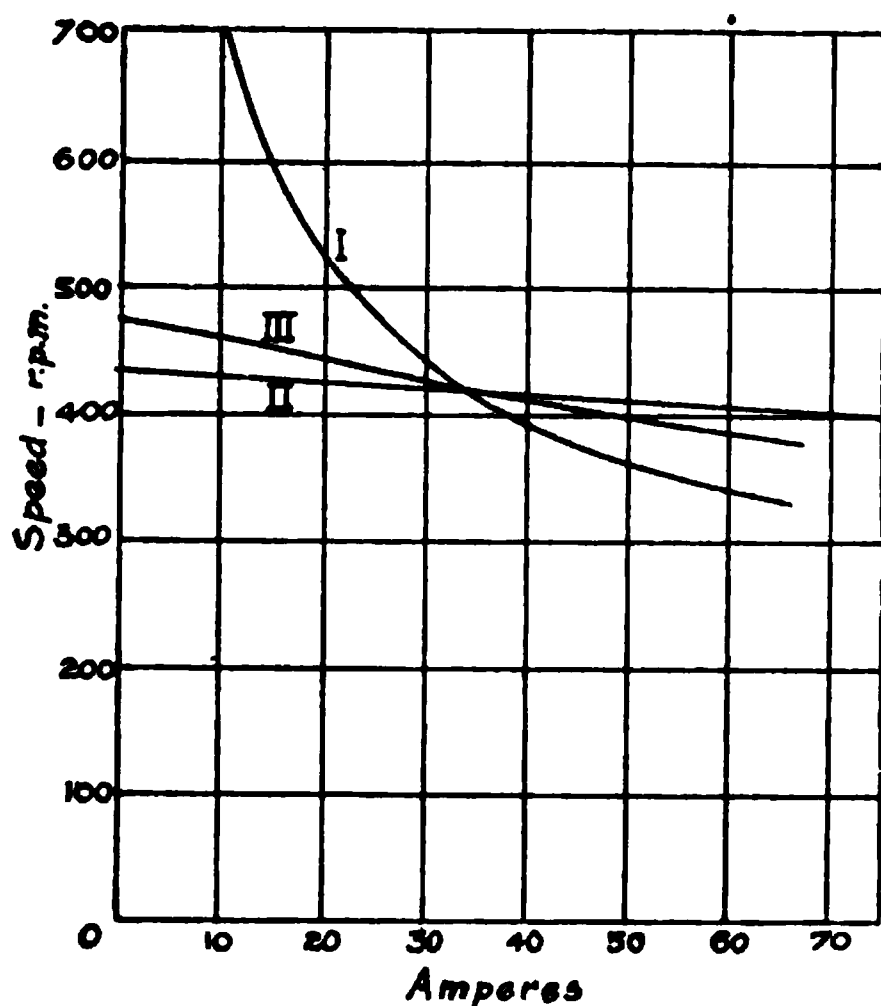
where n is the speed of the armature in revolutions per minute, E the voltage at the terminals of the motor, e the voltage drop in the motor, and p , T , Φ have the same significance as above. For a given motor

the speed is, therefore, proportional to the ratio : $\frac{\text{counter-E.M.F.}}{\text{flux}}$.

The speed-current curves given in Fig. 10 have been calculated for the above motors, and by combining these curves with those in Fig. 8 we obtain the speed-torque curves of Fig. 11, which represent the dynamical performance of each motor.

Comparing the dynamical performance of each type of motor with that of the urban and suburban trains given in the preceding chapter, we find that the *series motor possesses several advantages* over the other types, viz. (1) large starting torque, (2) high free-running speed, (3) speed automatically decreases on “up” gradients, thereby avoiding the large increase in output which would occur if the speed were constant. In addition to these advantages on the dynamical side, the series motor has an important advantage on the electrical side, viz. that the *division of load between several motors in parallel* is only slightly affected by (a) differences in the diameters of the driving wheels, and (b) differences in the speed-curves of the motors.

To illustrate this point let us consider a car equipped with two series motors, each having a speed-curve identical with curve I, Fig. 12a, one motor (A) driving a pair of wheels 30 in. in diameter, and the other



FIGS. 10 and 11.—Speed-current and Speed-torque Curves for Series (I), Shunt (II), and Compound (III) Motors.

motor (B) driving another pair of wheels 29½ in. in diameter. For a given speed of the car, the speed of armature *B* will be $(30/29.5=)1.017$ times that of *A*. The current input to each motor (when connected in

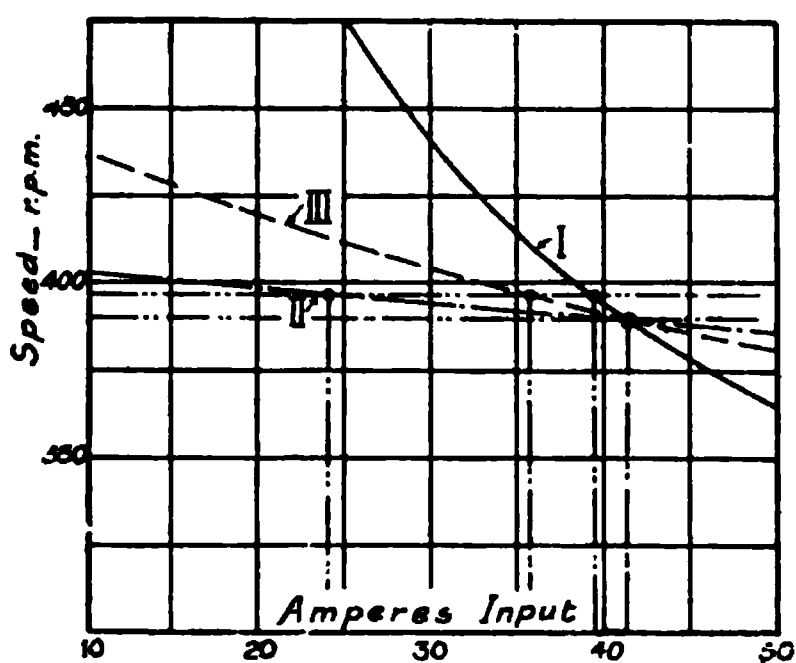


FIG. 12a.

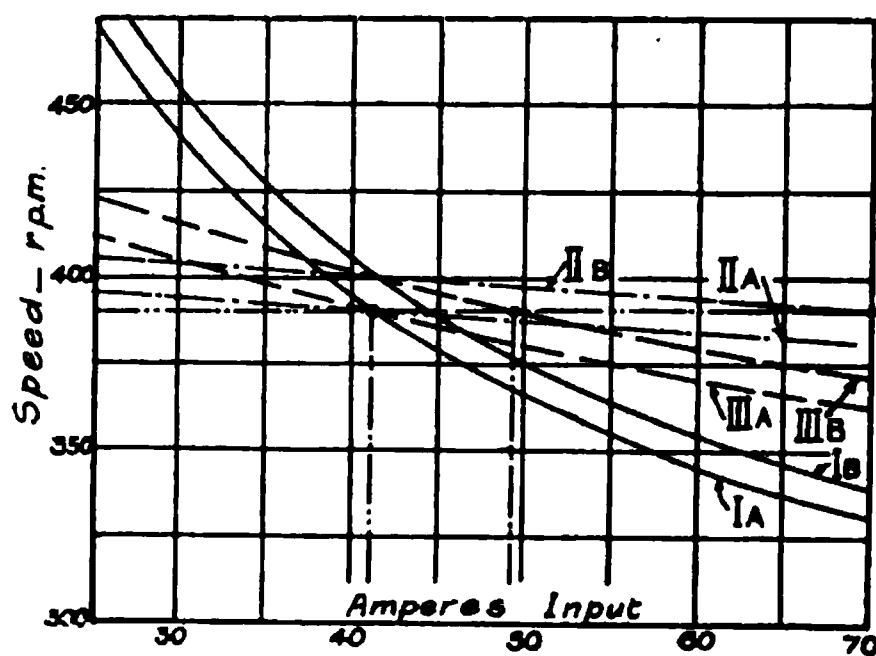


FIG. 12b.

parallel) will be the currents corresponding to these speeds on the speed-curve I (Fig. 12a). Thus, if armature *A* is running at 390 r.p.m., then the speed of armature *B* will be $1.017 \times 390 = 397$ r.p.m. These speeds correspond to currents of 41.5 amp. and 39.5 amp. respectively.

If the car were equipped with two shunt motors having speed-curves identical with curve II (Fig. 12a), then we could obtain the current input to each motor in exactly the same manner. Thus, if the speed

of armature *A* is 390 r.p.m., the speed of *B* will be $1.017 \times 390 = 397$ r.p.m., and the currents corresponding to these speeds on speed-curve II are 41.5 amp. and 24.2 amp. respectively. We observe in this case that the motors are loaded very unequally.

Let us now consider the effect of the speed-curves of the car motors not being identical. If all the wheels are assumed to have the same diameter, then, for a given speed of the car, the armatures will run at equal speeds. The current input to each motor will be obtained from the point on each speed-curve which corresponds to this speed (see Fig. 12*b*). If the wheels differ in diameter, then we proceed in the manner indicated above.

Summarising these results, and incorporating with them the values obtained for compound motors, we have :

(*a*) Speed-curves of car motors identical (Fig. 12*a*), driving wheels of unequal diameter :

Type of Motor.	Diameter of Driving Wheels (in.).		Speed of Armatures (r.p.m.).		Current Input (Amperes).	
	Motor A.	Motor B.	Motor A.	Motor B.	Motor A.	Motor B.
Series . . .	30	29.5	390	397	41.5	39.5
Shunt . . .	30	29.5	390	397	41.5	24.2
Compound .	30	29.5	390	397	41.5	35.8

(*b*) Speed-curves of car motors not identical (Fig. 12*b*), driving wheels of equal diameter :

Type of Motor.	Reference to Speed-curves. (Fig. 12 <i>b</i> .)		Speed of Armatures (r.p.m.).	Current Input (Amperes).	
	Motor A.	Motor B.		Motor A.	Motor B.
Series . . .	Curve IA	Curve IB	390	41.5	44.5
Shunt . . .	Curve IIA	Curve IIB	390	41.5	72
Compound .	Curve IIIA	Curve IIIB	390	41.5	49.5

In the above discussion our comparisons have been based upon the performance curves of the various types of motors, but in railway service there are certain features in the operating conditions which cannot be predetermined from the performance curves. Thus, a traction motor is liable to be subjected to sudden pressure-rises in the supply circuit, such as may occur when a heavy current or a short-circuit is opened ; the motor is also liable to be subjected to brief interruptions of the supply circuit and the restoration of full voltage, such as would occur if cross-overs and section-insulators were crossed with power on. These conditions are, of course, peculiar to traction service, and therefore it will

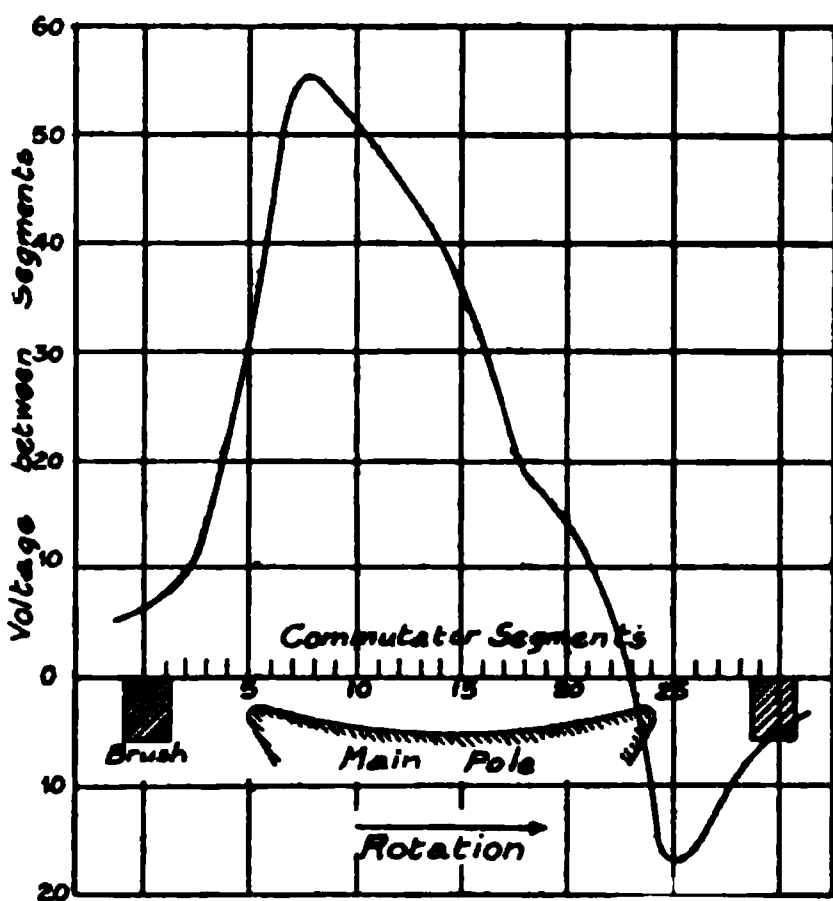
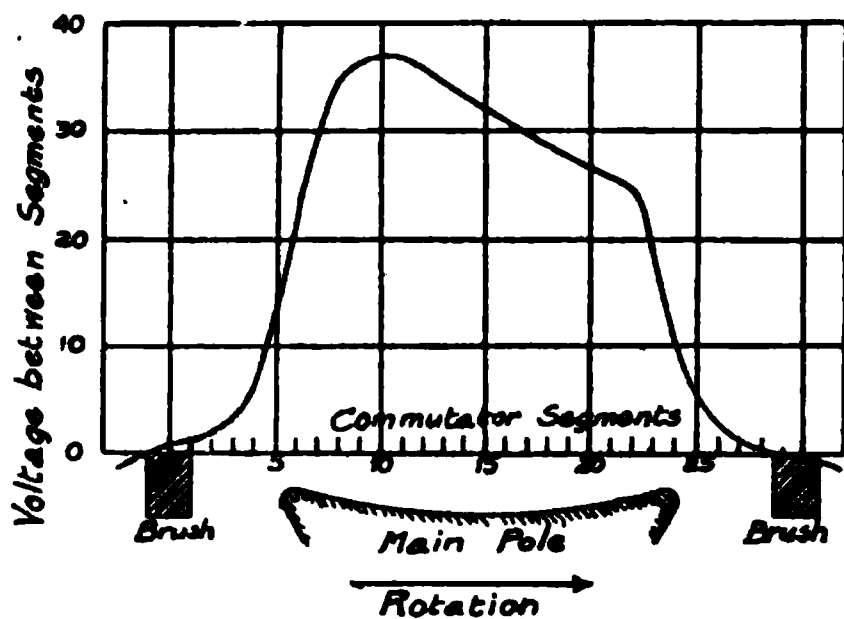
be desirable to consider how the operation of the different types of motors will be affected by them.

Dealing first with the **effects of pressure-rises**: when a motor is subjected to a sudden pressure-rise, the initial value of the current-rush will be determined by the impedance of the motor circuit, and the duration of this current-rush will depend on the rate at which the counter-E.M.F. of the motor is built up. The current-rush will, therefore, have a lower initial value, and will be of shorter duration, in series motors than in compound or shunt motors.

The commutation of this current will generally lead to sparking, and the operation of the motor can be considered as satisfactory provided that the sparking is not so vicious as to cause a flash-over at the brushes.

Now a "flash-over" is usually caused by an excessive voltage between the commutator segments in the vicinity of the brushes, this voltage being sufficient to maintain an arc between the segments when produced by sparking at the brushes: the arc is, therefore, drawn out across the commutator until it extends from brush to brush, thereby causing practically a short-circuit across the supply system.

The voltage between commutator segments in the vicinity of the brushes is largely influenced by armature reaction, and, considering only the case of a machine with the brushes in the neutral position, this voltage, for a given field-strength, will be the greater the stronger the armature reaction. This is shown by Figs. 13 and 14, in which are given curves representing the distribution of potential around the commutator, under various conditions of armature and field strengths, for a non-commutating pole machine.



FIGS. 13 and 14.—Distribution of Potential around Commutator of Non-commutating-pole Motors. Fig. 13—Strong field, weak armature. Fig. 14—Weak field, strong armature.

It is apparent that a shunt motor of ordinary design will be more sensitive to pressure-rises than a series or a compound motor. The series motor, as designed for traction service, even without auxiliary commutating devices, is able to withstand sudden pressure-rises of a large amount (perhaps 60 to 70 per cent. or more above normal voltage), which, if applied to a shunt motor, designed without compensating windings, would certainly produce flash-overs.

Next, consider the **operation** of the motors **when the supply circuit**

is briefly interrupted and restored at full voltage. There is now a characteristic difference between a series and a shunt motor, as, with the latter machine, the counter-E.M.F. is maintained—but at decreasing value—during the interruption, while with the former machine the counter-E.M.F. ceases when the interruption occurs. On the restoration of the supply voltage, the shunt machine will have a certain counter-E.M.F., and the initial value of the current-rush will be determined by the resultant-E.M.F. and the impedance of the armature circuit, in a similar manner to that above. In the series motor, however, the initial current-rush will depend entirely on the impedance of the motor circuit, but it will only be of very brief duration if the counter-E.M.F. is built up rapidly. Moreover, since the frames of traction motors are usually solid, the flux will not rise at the same rate as the current, and, consequently, the series motor will have to commute this fairly large current with a relatively weak field. The building up of the flux and the increasing counter-E.M.F., however, give rapidly improving commutation, so that, by suitable design, the motor will be able to withstand this operating condition without flashing-over.

The features in the design of a series motor to obtain this result are: (1) a relatively “strong” field and a “weak” armature (*i.e.* the field ampere-turns at rated load must be much greater than the armature ampere-turns); * (2) a liberal number of commutator segments; (3) a large neutral commutating zone; (4) the elimination of solid spool bodies and short-circuited turns in the field coils (so that the flux cannot be retarded by eddy-currents induced in these parts).

Series traction motors designed on these lines, without special commutating devices, will operate satisfactorily with interruptions in the supply circuit such as occur in service, and in order to produce a flash-over under these conditions a voltage of from 50 to 80 per cent. above normal is required. Of course, with a rough commutator or weak brush pressure, in combination with vibration, flash-overs may be produced with lower voltages, especially when the machine is running at high speeds.

In addition to the above features in the electrical design, there are other features in the electrical and mechanical design of traction motors, as well as in their construction, which differ from the standard practice with stationary motors, and which will now be considered in detail.†

Firstly, the motors usually drive the axles through gearing,‡ and must be located under the car, thereby necessitating a completely protected design.

Secondly, the motors must be capable of running under adverse

* In non-commutating-pole traction motors the field ampere-turns at the rated load are from two to three times greater than the armature ampere-turns, whereas, in stationary motors, values between 1.5 to 1.75 are usually adopted.

† These considerations refer to the type of motor suitable for tramway and suburban railway service and also for slow and moderate speed locomotive service.

As many features in the design and construction of tramway and railway motors are similar, it has been considered desirable to discuss them together.

‡ The object of the gear drive is to enable a motor of light weight and small overall dimensions to be used. Thus, a geared motor, rated at 170 H.P., 600 volts, 550 r.p.m., weighs 5150 lb., and can be used with 36-in. wheels; while a gearless motor (*i.e.* one with the armature direct on the axle) of similar output—170 H.P., 550 volts, 190 r.p.m.—weighs 12,000 lb. and requires wheels of a minimum diameter of 42 in.

FIG. 15.—B.T.H. (Type RGE 20) Commutating-pole Tramway Motor.

FIG. 16.—Dick-Kerr (Type DK 20) Commutating-pole Tramway Motor. This motor has ring lubrication for the armature bearings.

FIG. 19.—Dick-Kerr 250-H.P. Commutating-pole Railway Motor. This motor is provided with ring-lubricated armature bearings.

FIG. 18.—B.T.H. (Type GE 235) Commutating-pole Railway Motor. Designed for self-ventilation and tap-field control.

conditions (*e.g.* with unequal air-gaps between armature and pole-pieces, due to wear of bearings) for lengthy periods without overhauling.

Thirdly, the motors must operate satisfactorily in either direction of rotation without adjustment of the brush gear.

Fourthly, the rotating elements must be designed to withstand the centrifugal forces corresponding to the maximum speed of the train or car.

Fifthly, motors for use on motor-coach trains and tramcars should be designed for light weight.

FIG. 17.—Westinghouse Commutating-pole Tramway Motor with box-frame of pressed steel.

(NOTE.—The two halves of the frame are pressed from plate of light section. They are arranged with a tightly fitting overlapping joint, and are bolted and riveted to a pressed steel yoke (of high-permeability steel), which forms the principal magnetic portion of the frame. The axle caps, axle guard, commutator cover, and suspension bar also consist of pressed steel. The motor illustrated is rated at 48 H.P., 600 volts, 600 r.p.m., and weighs 2100 lb., the weight being 580 lb. lighter than that of a motor, of similar rating, with a cast-steel frame.)

The **electrical design** of the motors, therefore, involves the use of a two-circuit winding on the armature * and the brushes fixed in the geometrical neutral position. In order to obtain good commutation with the brushes in this position, it is necessary either to design the machine with a relatively strong field (*i.e.* a saturated magnetic circuit)

* For a full discussion on the characteristics and properties of two-circuit windings, the student is referred to *Armature Windings* (Hobart & Ellis), and *The Dynamo*, vol. 1 (Hawkins & Wallis). (Published by Whittaker & Co.)

The properties of the winding, which render it valuable for traction motors, are : (1) the electrical balance of the two circuits, even with unbalanced magnetic circuits ; (2) multipolar machines can be operated with only two sets of brushes.

and a weak armature, or to adopt normal values for these quantities and fit commutating poles. The latter expedient is usually adopted in modern motors, as machines with commutating poles have several advantages over machines without this feature, but we must defer the discussion of this point until later.

It is standard practice to adopt four poles on all geared tramway and railway motors, and, with a two-circuit winding, the motors can be operated satisfactorily with only two sets of brushes, which can be located

FIG. 20.—B.T.-H. Tramway Motor with lower half of frame lowered for inspection of armature.

in a position accessible from the car floor. On the other hand, if four sets of brushes were used it would be necessary to run the car over an inspection pit to inspect or renew any brushes in the lower sets.

The **mechanical requirements** are satisfied by excluding cast iron from the construction of the motors and using cast steel or malleable iron in its place. Thus the frame, frame-heads, commutator-shell, and clamping-rings are of cast steel,* while the armature flanges are of malleable iron or cast steel.

* The Westinghouse Co. have recently introduced a 40-H.P. tramway motor (illustrated in Fig. 17) with the frame and a number of mechanical parts constructed of *pressed steel*. For details, see the *Electric Journal*, vol. 11 (1914), p. 581.

FIG. 21.—Arrangement of Bar Suspension for Tramway Motor (Westinghouse No. 220).

Two **types of frames** are in general use, viz. (1) the split-frame, which is standard for tramway motors,* and (2) the box-frame, which is used almost exclusively for railway motors. Typical views of split-frame and box-frame motors are given in Figs. 15 to 19. A split-frame motor is generally required for tramway work, as it is necessary to provide means for inspecting and changing the armature or bearings without dismantling the motor from the truck. By arranging the lower half of the frame to open downwards, as shown in Fig. 20, the armature can be handled in an inspection pit. The armatures of railway motors, however, are too heavy to be handled in this manner, and there is, therefore, no advantage in a split-frame; in fact, a split-frame is a disadvantage, since, for equal strength, it is heavier and less rigid than a box-frame, and is difficult to keep oil-tight at the joint near the axle bearings. The only occasion in railway motors where a split-frame may be necessary is for the "gearless" motor, in which the armature is mounted directly on the axle.

With a **geared motor**, the centre-line of the armature must be maintained parallel to, and at a fixed distance from, the axle of the driving wheels. This is accomplished by supporting one side of the frame on the axle. Two axle bearings are, therefore, required on the frame, as shown in Figs. 15 to 19. The other side of the frame is supported from the truck, either by a "nose" on the frame resting on a bracket attached to the transom † (see Fig. 280, p. 334) of the truck, or by a transverse bar (bolted to the frame) carried on springs from the side frames of the truck, as shown in Fig. 21. The former method—called "**nose suspension**"—is adopted with railway motors (from 75 H.P. upwards), and the latter method—called "**bar suspension**"—with tramway motors.

The **armature bearings** are located in frame-heads or housings which, in split-frame motors, are carried in cylindrical seats between the two halves of the frame, and in box-frame motors are bolted to recesses in the ends of the frame. The lubrication of the armature and axle bearings is generally on the pad principle, using wool-waste saturated with oil, although in some motors oil-rings are used for the armature bearings. In railway motors the armature bearings are countersunk into the commutator and the back-end armature flange, since by this construction the limited space between the wheels is utilised to the best advantage for electrical purposes (see Fig. 22).

The usual **method of transmitting the power from the motor to the axle** is through single-reduction spur gearing, the gear ratio being generally limited to a maximum value of 5:1. A single set of gearing is adopted for motors up to about 250 H.P., but where larger motors are used on electric locomotives it is usual to fit twin-gears (see Fig. 310, Chapter XVII, p. 377).

The **pinion** is usually of forged steel, with or without heat treatment, and is fitted to a taper on the armature shaft. The width of face varies from 4½ in. to 6 in., and the tooth pitch varies from 3 to 1½ (diametrical).

The **gear-wheel** may be of cast steel (in which case either a split or a solid type can be used), or of forged steel, heat treated; but in the

* The box-frame has recently been introduced for tramway motors, the introduction being due to the increased reliability of modern commutating-pole motors and the improved methods of lubricating the armature bearings.

† The transom is the cross member of the truck from which the bolster is supported (see p. 313).

latter case only the solid type is available. The solid type of gear is now superseding the split type, as the increased life of heat-treated gears (compared with cast-steel gears), combined with the better mechanical

FIG. 22.—Longitudinal Section of Railway Motor.

construction of the solid gear, more than compensate for the difficulties connected with the fixing and removing of this type of gear.

During recent years the manufacture of gearing for traction service

FIG. 23.—Gears and Pinions for Tramway Service (left); Heavy Suburban Railway Service (centre); and Light Railway Interurban Service (right). (Tool Steel Gear and Pinion Co.).

has received considerable attention, and, in consequence, gearing of high quality and long life is now obtainable. The principal feature in the manufacture of modern gearing is the process of heat treatment

to which the gears and pinions are subjected in order to obtain teeth with a hard surface and a tough centre. With some processes, a surface of exceptionally hard tool-steel is obtained, having a thickness of from $\frac{1}{8}$ in. to $\frac{3}{16}$ in. The heat treatment is, of course, given after the machining operations have been completed.

The advantages of heat treatment, in connection with gearing, will be apparent from an examination of Table VI, in which the properties of gearing, with and without heat treatment, are compared.

In Fig. 23 are shown typical gears and pinions (manufactured by the Tool Steel Gear and Pinion Co., Cincinnati) for tramway and railway service. It will be observed that all the gears are of the solid type. The process of manufacture is such that the teeth have a hard tool-steel surface and a toughened centre.

The gearing in the centre of the illustration is of interest, as it refers to the gears and pinions which are in service on the suburban lines of the London and South-Western Railway. The gear has a pitch-circle diameter of 30.5 in., a face of 7.5 in., and weighs 565 lb. The pinion has a pitch-circle diameter of 10.8 in., and weighs 113 lb.

The gear case is either of malleable iron or of pressed steel, and is bolted to lugs on the frame of the motor, as shown in Figs. 15 and 18.

Since the location of the motors under the car necessitates a completely protected construction, we should expect the machines to have somewhat poor thermal characteristics. By suitable design, however, it is possible to obtain a *self-ventilated machine*,* having fairly good thermal characteristics, without departing from the completely protected construction. The ventilation is effected by means of a fan at the back of the armature, in conjunction with longitudinal ventilating ducts in the commutator and armature core.

The air may be circulated through the motor by the series system, or by the parallel system.† A diagram, showing the series system of ventilation applied

FIG. 24.—Diagram showing the Circulation of Air (Series System) in a Self-ventilated Traction Motor.

to a tramway motor, is given in Fig. 24. In this system the air enters the motor through a screened hood *I* at the top of the frame (pinion end); it passes over the surface of the armature and field coils, then

* The *self-ventilated* type of machine should be distinguished from the *forced ventilated* type, which is of the ordinary construction with the addition of forced ventilation from an external blower.

† For a complete discussion on the systems of ventilation for traction motors see *The Electric Journal*, vol. 13 (1915), p. 204; article by Mr. R. E. Hellmund on "Railway Motor Ventilation."

TABLE VI
COMPARATIVE PROPERTIES OF VARIOUS GRADES OF GEARING.

Grade.	Heat Treatment.	Remarks.	Ultimate Tensile Strength.	Elastic Limit.	Elongation (2-in. test piece).	Reduction in Area.	Relative Hardness.	Relative Average Initial Cost.	Relative Life of Gears (based upon guaranteed figures).
Cast steel.	None.	Medium carbon.	tons per sq. in. 27-32	tons per sq. in. 11-15	per cent. 18-20	per cent. 20-30	Brinell scale. 121-155	1.0	1.0
Forged steel.	None.	Medium carbon.	31-38	16-20	18-20	35-45	176-196	1.1	1.25
Forged steel.	Oil tempered.	High carbon. Uniform structure throughout.	49-54	36-38	10-15	25-35	300-360	1.4	2.5
Forged steel.	Special.	Medium carbon. Uniform structure throughout.	62-67*	62-67*	..	..	420-600	2.0	3.5
Forged steel.	Special.	Hardened high-carbon surface. Tough low-carbon core.	Cannot be determined, as structure of metal after treatment does not allow a test piece to be obtained.				555-650	2.0	5.0

* Obtained from treated test bars.

through the longitudinal ventilating ducts in the commutator and the armature core, and is finally expelled through the fan *F* and the openings *O* in the pinion-end frame-head. A baffle plate *B* separates the space around the fan from the armature and field coils, and ensures the circulation of the air in the manner described.

This method of ventilation has been applied by the British Thomson-Houston Co., the General Electric Co., and the Westinghouse Companies to tramway and railway motors. Fig. 25 illustrates a B.T.-H. type GE 235 railway motor in which this method of ventilation is adopted. The hooded inlet and the outlets can be clearly seen. The fan and the pinion-end frame-head are designed so that a baffle plate is unnecessary.

The **armature winding** is exclusively of the two-circuit variety, and the coils are located in open slots in the punchings. The number of

FIG. 25.—B.T.-H. (GE 235) Self-ventilated Railway Motor with Pinion-end Frame-head removed.

turns per coil will, of course, vary with the size of the motor. For tramway motors up to 60 H.P., from two to six turns per coil are used, according to the speed required; but for railway motors, from 75 H.P. upwards, it is generally only possible to use one turn per coil. Where one or two turns per coil are adopted, the conductors consist of rectangular copper bar (in order to obtain a high space factor in the slot), and in these cases the insulation consists principally of mica.

The number of coils per slot is usually either three or five, although, in some cases, four coils per slot are used; but this number, in a four-pole machine, requires a dead-coil.* When five coils per slot are adopted in large railway motors, the slots become fairly wide, and, at high flux densities in the air-gap and armature teeth, eddy-currents may be generated in the conductors. Some manufacturers provide against this by

* This is one of the peculiarities of the two-circuit winding, and is discussed fully in the works previously mentioned. In four-pole machines, the number of coils per slot may be 1, 3, 5, 7, &c., for symmetrical windings; but if 2, 4, 6, 8, &c. are used, then there will be one dead-coil in the winding.

splitting the slot portion of the conductor and introducing a double twist or cross-over, as represented in Fig. 26.

The **end connections** of the coils are usually protected from dust and oil by hoods or coverings of canvas, which are bound into place

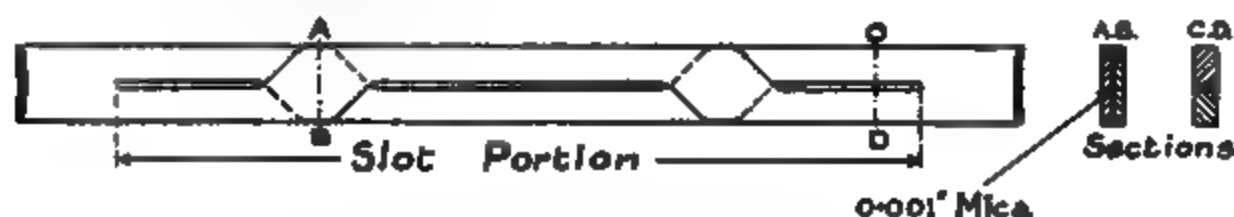


FIG. 26.—Diagram of Double Cross-over in Armature Bar.

after the winding has been completed. These coverings can be seen in the view of a completed armature in Fig. 27.

On account of the high peripheral speeds (approaching in some cases 8000 ft. per min.) and the large centrifugal forces to which the armature winding of a railway motor is liable to be subjected, the **binding bands** are an important item in the design of the armature.

The **commutator** for a tramway motor is similar in construction to that for a stationary motor, i.e. the back V-ring is solid with the shell, and the front V-ring is held in position by a recessed ring nut. With railway motors, however, the commutator must be designed to accommodate the internal projecting portion of the frame-head carrying the commutator-end armature bearing, and special precautions must be taken to prevent oil from reaching the interior. The shell and *front* V-ring are therefore combined, while the back V-ring is held in position by bolts, as

shown in Fig. 22. The mica between the segments is recessed to a depth of $\frac{3}{8}$ in. in order to eliminate commutation troubles due to "high mica."

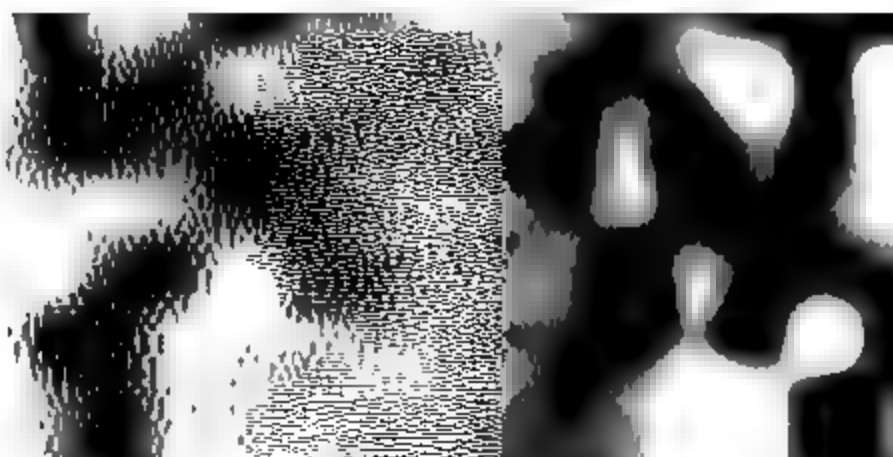


FIG. 27.—Armature of Self-ventilated Railway Motor.

In modern traction motors the **brush-holders** are fixed to mica-insulated supports which are bolted to

machined seats on the frame. The brush-holders are arranged for radial adjustment and also means for adjusting the brush pressure.

The **brush pressure** required for a traction motor will be greater than that necessary for stationary motors, on account of the increased vibration. For motors operating at low speeds, over good track, a brush pressure of from 2 to 3 lb. per sq. in. is satisfactory, but for high speeds the pressure must be increased to about 5 lb. per sq. in.

The **main poles** are built of soft steel laminations, but the **commutating poles** are solid steel forgings.

In tramway motors the **field coils** for the main and commutating poles are former wound, the conductor consisting either of rectangular wire, insulated with asbestos and cotton coverings, or of flat copper

strip insulated between turns with asbestos tape. The coils are generally "mummified"—that is, impregnated with a bitumen compound—in order to obtain a coil of good thermal characteristics, combined with non-hygroscopic properties.

In railway motors, on account of the larger weight of copper in the field coils and the smaller length available for the winding, the main field coils are, in some motors, wound on a spool body of cast brass. A strip conductor is used, insulated between turns with asbestos tape, and from the spool body with mica. The commutating field coils are former wound in the same manner as those for tramway motors. An interior view of a modern Westinghouse railway motor is shown in Fig. 28, and it will be observed that, in this motor, the main field coils, as well as the commutating field coils, are former wound. The armature for this motor is shown in Fig. 27.

Although the above description and illustrations refer to standard 600-volt motors, the frame, poles, armature core, and me-

FIG. 28.—Interior of Commutating-pole Railway Motor (British Westinghouse Co.).

chanical details of construction may also be taken as typical of **high voltage motors**, the constructional differences being in the commutator, brush gear, armature, and field windings. The insulation at these parts must be increased and additional leakage surface provided at the commutator and brush gear, while it is also desirable to insulate the interior of the frame in the vicinity of the commutator. The number of segments in the commutator must be increased in order to obtain a suitable value for the average voltage per segment and to reduce the liability to flash-over.

Commutating-pole motors are now largely adopted on tramways and railways, since machines of this type have many advantages over those of the non-commutating-pole type. Firstly, sparking at the brushes is practically eliminated at all loads and speeds, thereby enabling a soft brush (of low contact resistance) to be used on grooved commutators. Under these conditions the wear of the commutator and brushes will be considerably less than that in ordinary machines, while the losses at the commutator will also be lower.

Secondly, in the commutating-pole design, a lower ratio of the field ampere-turns to the armature ampere-turns can be adopted than in the ordinary design, and, as a consequence, the motor can be built for a lower flux and an increased armature strength, although the full advantage of the latter cannot usually be obtained, as a machine with high armature reaction and weak main field would be sensitive to pressure rises and interruptions in the supply circuit. The lower flux will result in lower core losses, which, in combination with the lower commutator losses, will lead to an improvement in the efficiency and heating.

Thirdly, a range of economical running speeds is possible by "tap field" control *—that is, tappings are brought out at various points in the field winding, by means of which different field strengths can be obtained for a given armature current. This method of control will therefore result in a lower energy consumption.†

Fourthly, since perfect commutation is obtained, the average voltage between commutator segments may be higher than that in machines of the non-commutating-pole type, and, in consequence, the motors can be built for higher voltages. Railway motors are now operating at voltages of 1200, 1500, and 1875 volts on a single motor, and two motors in series on circuits of 2400, 3000, and 3750 volts. In fact, the development of high-voltage continuous-current traction has only been made possible by the commutating-pole traction motor.

Fifthly, the tendency to "flash-over" is much less in a commutating-pole traction motor than in a non-commutating-pole machine, although,

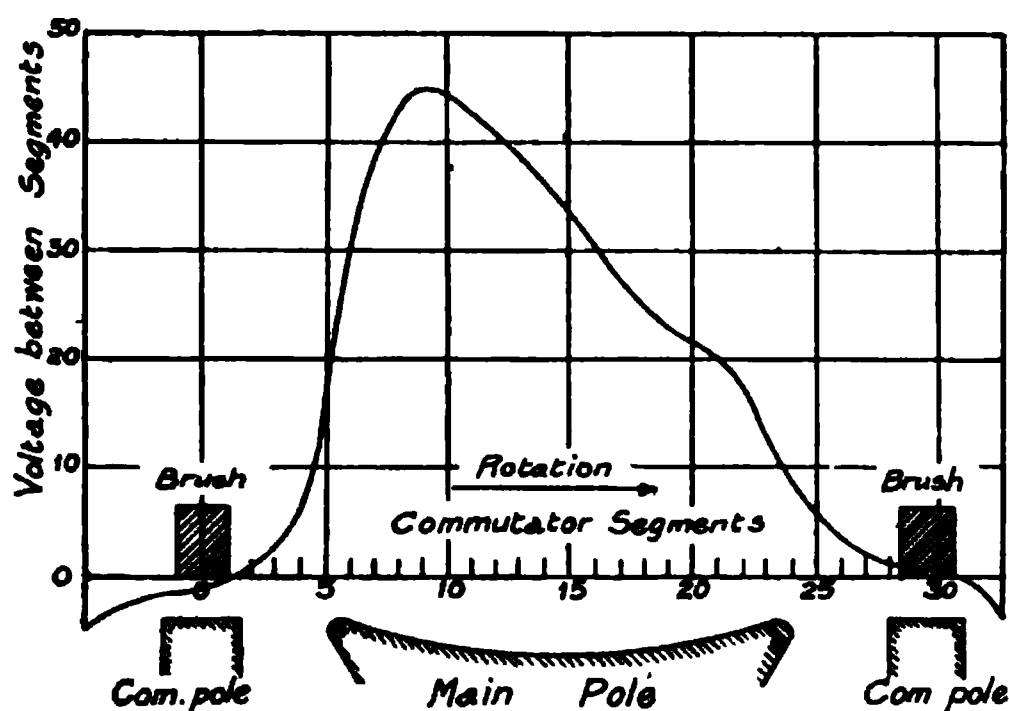


FIG. 29.—Distribution of Potential around Commutator of Commutating-pole Traction Motor.

as already stated, the armature reaction in the former machine is usually higher than that in the latter. The effect of the commutating pole on commutation is shown in Fig. 29, which should be compared with Figs. 13, 14, when it will be observed that the voltage between the segments in the immediate vicinity of the brushes has been reduced.

Although the commutating-pole traction motor is designed with a lower flux, and, therefore, less field turns than the non-commutating-pole motor, the impedance will probably be greater than that of the latter machine on account of the commutating field coils. The current-rush, corresponding to a given pressure-rise or interruption of the supply, will, therefore, be lower, while the commutation will be better, so that the tendency to flash-over will be less. Generally, it will be found that the commutating-pole motor will have a flash-over voltage of from 25 to 30 per cent. greater than that of the non-commutating-pole machine.

RATING

On account of the variable nature of the load on motors operating on tramways and suburban railways, they cannot be rated on a continuous basis in the same manner as stationary motors, and consequently the temperature rating is arbitrarily based on the **one-hour**

* A similar result would be obtained by shunting the field coils, but for traction work the shunt would require to be of the inductive type, as a non-inductive shunt would take practically all the current on a sudden increase in the load.

† A full discussion of this method of control is given in Chapter VIII, and calculations of energy consumption are given in Chapter XIX.

load,* which will produce a temperature rise of 75° C. (by thermometer) when the motor is tested on a stand.†

This method of rating traction motors was introduced in the standardisation rules of the American Institute of Electrical Engineers in 1902,‡ and has been adopted by the principal manufacturers of traction equipment.

Although these tests do not give any indication of the temperature rise in service, they are sufficiently severe to ensure reliability in the operation of the motor under service conditions.

The **temperature rise in service** will naturally be influenced by the design of the motor, and will also depend on the class of service and the duration of the lay-over periods. For urban and suburban service, with short lay-over periods, the temperature rise of a non-ventilated motor, at the end of a day's running, will generally be about 50° to 60° C., if the accelerating current corresponds to the rated load of the motor.§ The temperature rise of a ventilated motor under similar conditions will be lower than this, on account of the better ventilation at free running speeds and the efficient cooling which takes place during coasting.

Effect of commutating poles and ventilation on rating.—Since the output of a commutating machine is limited by (1) sparking and (2) heating, it will be apparent that if these limits are both reached at the rated load, the addition of commutating poles to the machine will require a redistribution of the copper in order to obtain an increased output; and, even under these conditions, the output will be limited by heating rather than commutation. Hence, the self-ventilated traction motor was the natural sequence to the commutating-pole motor, in order that the full advantage of the commutating poles might be obtained. The increased rating of the modern motors enables a motor of large output to be used on motor-coach trains (where usually the size of the motor is limited by the diameter of the wheels). Thus, we now find self-ventilated motors, rated at 250 H.P. and 275 H.P., installed on motor-coaches, while, with the older motors, the output was limited to about 200 H.P.

For locomotives, however, the **forced ventilated motor** is preferable, since, by the use of an external blower, the quantity of cooling air can be adjusted to suit the conditions. Moreover, a machine specially designed for supplying an air-blast will, obviously, be more efficient in its operation than a fan fitted to the armature of the motor. The blower is usually driven by a small motor, and generally supplies air to all the motors on the locomotive. This method of ventilation would not be desirable with motor-coach trains, since a motor-driven blower, air-ducts, &c., would be required for each motor-coach, thereby increasing the train weight and forming an item in the maintenance charges which is unwarranted for suburban traffic.

* Motors for operating on long-distance railways, where the free running conditions represent practically a steady load, will obviously be rated on a different basis.

† See Chapter VII for details of this test.

‡ See *Transactions of American Institute of Electrical Engineers*, vol. 19, p. 1803. The rules were revised in 1914 and 1915 (see *Proceedings*, vol. 33, p. 1281, and vol. 34, p. 1935), and the section relating to railway apparatus is given in Appendix II.

§ The methods of estimating the temperature rise in service from factory tests are discussed in Chapter VII.

Motors for operating on high voltage circuits require larger leakage surfaces at the commutator and brush gear in addition to extra insulation on the armature and field coils. This extra insulation, combined with the smaller size of conductor, will give a lower space-factor in the armature and field coils, so that the rating of a given frame, when wound for high voltage, will be lower than that of the same frame when wound for, say, 600 volts. Generally a 10 per cent. to a 15 per cent. reduction in the 600-volt rating will be necessary when the motor is wound for 1200 volts.

Method of obtaining several ratings from a given frame.—In tramway motors it is possible to obtain several ratings from a given size of frame by varying the number of turns in the armature coils; the number of slots, number of commutator segments, dimensions of armature core, commutator, poles, &c., being constant, while the number of turns and size of conductor on the field coils varies with the rating. For example, a certain motor with 6 turns per armature coil and 175.5 turns per field coil is rated at 28 H.P., 500 volts, 350 r.p.m., 53 amps.; with 4 turns per armature coil and 144.5 turns per field coil, the rating is 37 H.P., 500 volts, 500 r.p.m., 68 amps. An intermediate rating could be obtained by using 5 turns per armature coil, and a higher rating (about 44 H.P., 670 r.p.m.) by using 3 turns per armature coil, but the latter rating would probably require a re-design of the armature core and commutator. The weight of the motor is substantially the same for each rating, while the weight per H.P. decreases as the rating increases, so that at the high-speed rating the machine could be called a “**light-weight**” motor. These light-weight, high-speed motors are suitable for operating on certain high-speed services, but are not suitable for congested city traffic, since not only would the energy consumption be excessive under these conditions, but the gear ratio required for the latter class of service would be larger than that which could be accommodated in a standard gear-case.

In addition to these service limitations, there are other limitations in the design of the motor which prevent a too general application of this principle. Firstly, since round wire is generally used for these armatures, the slots for the various ratings will differ in size. Secondly, the brush gear and commutator must be designed for the maximum rating. Thirdly, if we assume the flux to be constant.* at the various ratings, then the core loss will increase as the rated speed increases, and since only a certain number of watts can be dissipated by the frame, either the armature copper loss must be reduced or a special armature core used. Generally, the ampere-conductors on the armature at the rated load will have to be decreased as the rated speed is increased, and consequently the torque at rated load will decrease as the rating increases.

A self-ventilated motor will be able to dissipate a greater loss at the higher speeds, and hence the rating will increase at a greater rate than that of a non-ventilated motor, but the service limitations will influence both machines to practically the same degree.

Effect of the wheel diameter and gauge on the rating.—It is apparent that with the usual method of mounting motors on tramcars and motor-coaches, the size of the motor, and therefore the rating, is

* The flux at the lower ratings will have to be decreased slightly on account of the lower space-factor of the field winding.

limited by (1) the diameter of the driving wheels, (2) the gauge of the track. The maximum vertical dimension of the motor, and also that of the gear-case, is fixed by (a) the clearance between the bottom of these parts and the road surface, and (b) the clearance between the top of the motor (with gear-case) and the underside of the car floor. With a given size of frame these clearances will decide the diameter of the driving wheels, the standard size of which, on tramcars, is usually 30 in. in this country, and 33 in. in America. In obtaining the clearance between the bottom of the motor and the road surface, due allowance must be made for the wear of the wheel tyres. This has to be carefully considered with the large motors adopted on some tramways, and in some instances the diameter of the wheels must be increased to obtain the full life from

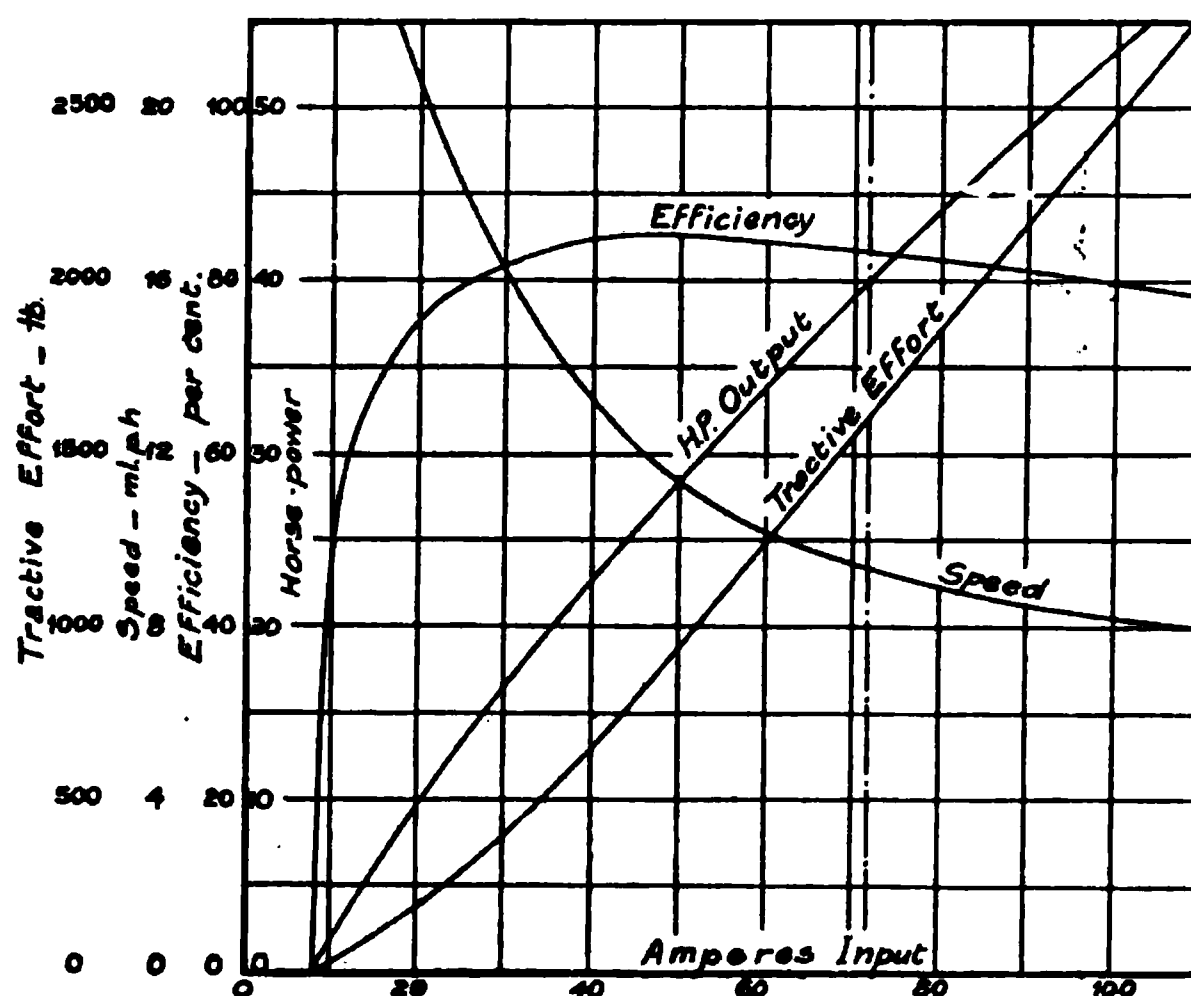


FIG. 30.—Characteristic Curves of 40 H.P., 500 volt, 500 r.p.m. Commutating-pole Tramway Motor (30-in. wheels, 4.73 : 1 gear ratio).

tyres. Thus, with the Westinghouse No. 220 (42 H.P.) motor (which is largely used on the L.C.C. tramway system), the bottom clearance with 30-in. wheels is 2 in., which does not allow the full life to be obtained from the tyres; hence it is desirable to adopt larger wheels having a diameter of at least $31\frac{1}{2}$ in. when new (see Fig. 21).

On the electrified lines of our suburban railways, where motor-coaches are used with standard rolling stock, the wheel diameter is usually about 42 in. to 43 in., and this diameter does not present a limiting feature in continuous-current equipments, since a motor rated at about 300 H.P. could be accommodated. The wheel problem on the underground and tube railways is very different, as it is necessary to adopt small wheels on account of the limited headroom. On the (London) District and Metropolitan Railways, 36-in. wheels are used on the motor-coaches with 230 H.P. motors, the clearance between motor and top of track rails being $4\frac{1}{2}$ in., and that between the motor and negative (central) conductor rail being 3 in. The same size of wheel and motor

is used on a large number of the tube railways, but in this case it has been necessary to raise the floor above the motor trucks.

The effect of wheel diameter on the motor rating is shown in a striking manner in the special motors developed for the low floor centre-entrance cars which have been introduced on some American tramways.* In some cases the top of the car floor is only 30 in. above the rails, and special two-motor bogie trucks with 24-in. wheels have had to be adopted. The use of these small wheels required a special design of motor, the rating of which is 30 H.P., while that of a standard motor, running at the same speed and suitable for 33-in. wheels, is 50 H.P.

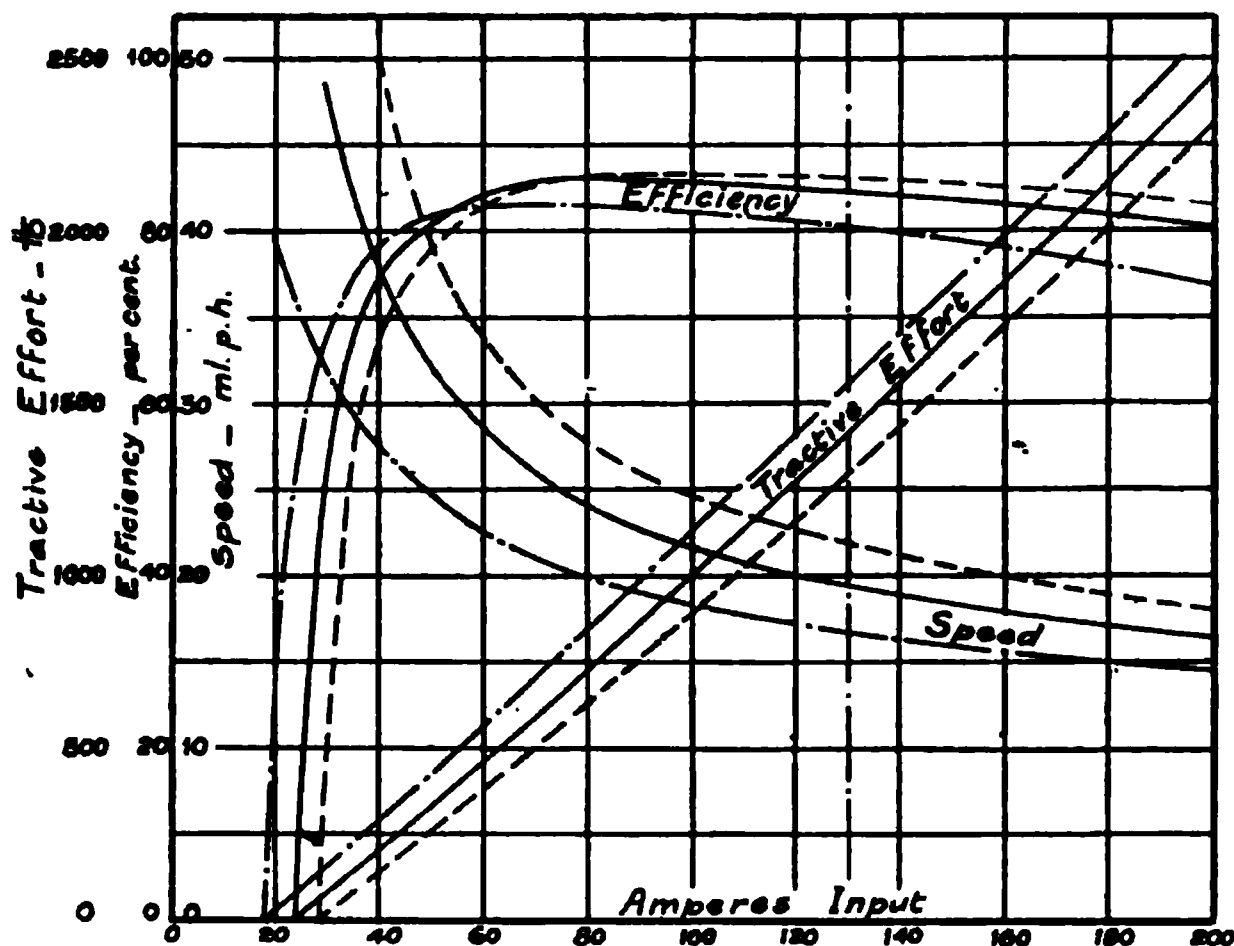


FIG. 31.—Characteristic Curves of 75 H.P., 500 volt, 585 r.p.m. Commutating-pole Railway Motor designed for Tap-field Control. NOTE.—The full-line curves refer to normal-field, the dotted curves refer to full-field, and the chain-dotted curves refer to minimum-field (43½-in. wheels, 3.88 : 1 gear ratio).

Some interesting comparisons between these motors are given in Table VII (p. 50).

The gauge of the track rails has also a considerable effect on the rating, but generally its limitations are only manifested in tramway motors, as practically all railway motors operate on standard gauge (4 ft. 8½ in.) and the influence of the gauge on the design is not evident to the same degree as in tramway motors.

Railway motors are designed so that the whole distance between the wheel hubs is occupied by the motor and gear (see Fig. 279, p. 333, and Fig. 310, p. 377). By adopting countersunk bearings, it is possible to utilise 75 per cent. of this distance for the armature and commutator, the remaining 25 per cent. being required for the gear, gear-case, and frame heads. The armature diameter can, therefore, be kept down to such dimensions that a 230 H.P. motor can be used with 33-in. wheels.

* In this connection see *Electric Railway Journal*, vol. 46, p. 4; *Electric Journal*, vol. 9, p. 825, vol. 10, p. 1013.

Where twin-gears have to be used, the motor has to be shortened and increased in diameter, so that larger wheels are necessary: for example, the 300 H.P. twin-gear motors on the 90-ton locomotive described in Chapter XVII require 48-in. wheels in order to obtain the requisite clearance between motor and track. On the other hand, if the whole space between the wheel hubs can be allotted to the armature and commutator—as in the New York Central locomotives—a motor of 550 H.P. can be used with 44-in. wheels.

In tramway practice the motor bearings are of the outboard (projecting) type, and the wheels are standardised to 30 in. or $31\frac{1}{4}$ in. With $31\frac{3}{4}$ -in. wheels, a 50 H.P. motor can be accommodated on standard

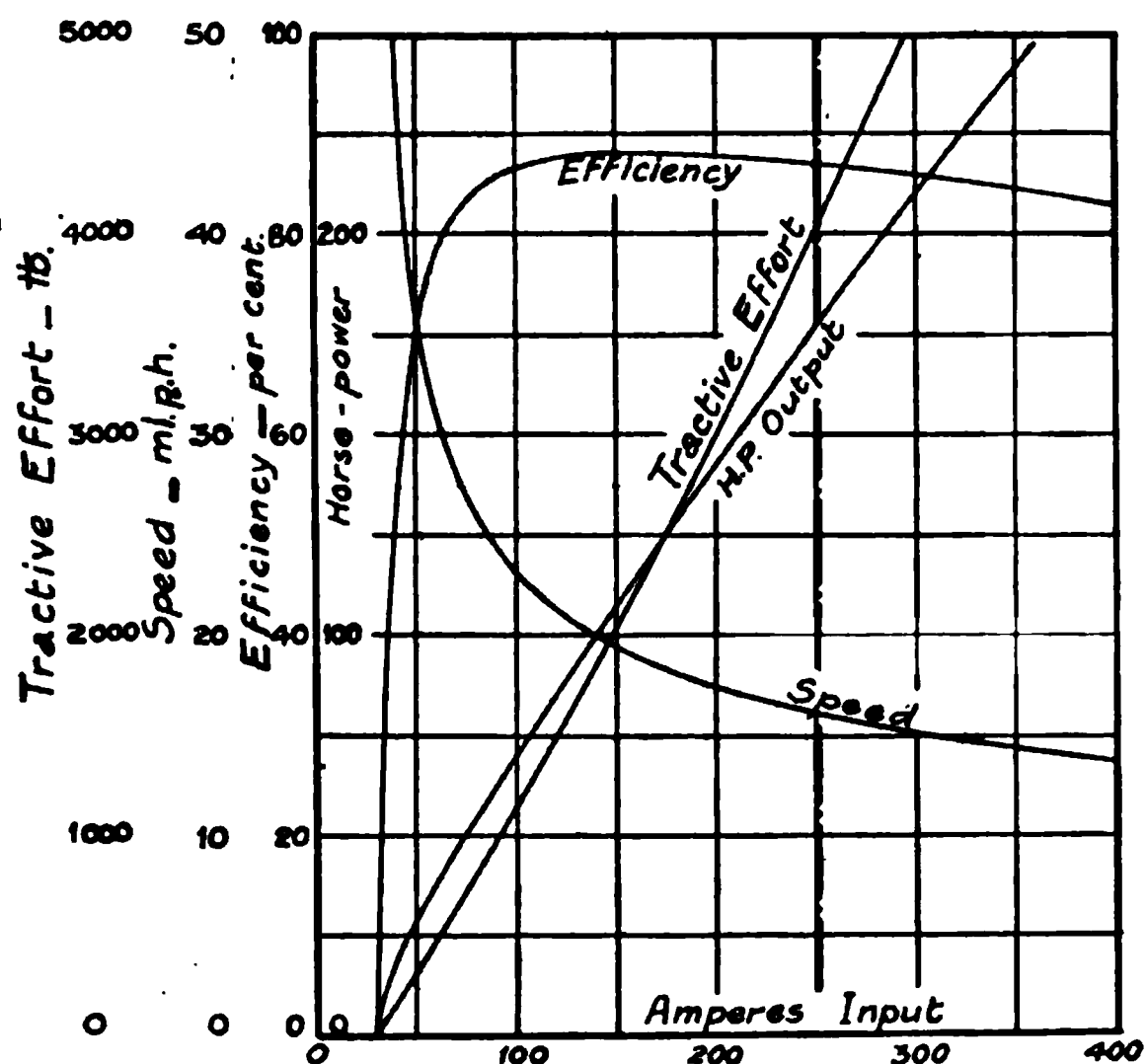


FIG. 32.—Characteristic Curves of 180 H.P., 600 volt, 520 r.p.m. Railway Motor (36-in. wheels, 3.5 : 1 gear ratio).

gauge, and a 40–45 H.P. motor on 4-ft. gauge. On 3 ft. 6 in. gauge it is possible to use a 35–40 H.P. motor with 30-in. wheels, and, in some cases, a 30–35 H.P. motor can be used on metre (3 ft. $3\frac{3}{8}$ in.) gauge; but where the gauge is below this (e.g. 3 ft.) the rating of the motor is limited to 20–25 H.P.

CHARACTERISTIC CURVES

Reference has already been made to the dynamical performance-curves of motors, and we give in Figs. 30, 31, 32, characteristic curves of typical tramway and railway motors, showing the efficiency, speed, and tractive-effort for a given gear ratio and diameter of driving wheels. The curves have been plotted in accordance with the standard method adopted for traction motors, and the manner in which the various quantities are obtained is considered in detail in Chapter VII.

TABLE VII

COMPARISON BETWEEN TRAMWAY MOTORS FOR 33-IN. AND 24-IN. WHEELS.

	Standard Motor for 33-in. wheels.	Special Motor for 24-in. wheels.
Designation of Motor	W—306	W—328
Rated H.P.	50	30
Weight of motor (lb.)	2400	1480
Weight of armature (lb.)	610	380
Weight per H.P. (lb.)	48	49·3
Ratio : armature diameter/gross core length	1·5	0·77
Height from rails to top of frame (in.)	30½	23½
Clearance between rails and bottom of frame (in.)	4½	3½
Gear ratio	4·6 : 1	3·56 : 1
Speed of armature at rated load and 500 volts (r.p.m.)	578	585
Speed of car at rated load and 500 volts (ml.p.h.)	12·38	11·65
Tractive-effort at rated load (lb.)	1500	960
Efficiency at rated load (including gearing) (per cent.)	83·8	81·1

CHAPTER V

SINGLE-PHASE TRACTION MOTORS

THE development of single-phase motors for electric traction has been confined almost exclusively to machines of the commutator type, as the single-phase induction motor is, inherently, incapable of exerting a large torque at starting. Moreover, the latter machine cannot be readily adapted for variable speeds, and, therefore, it is entirely unsuitable for traction service.* On the other hand, the commutator type of motor can be designed to have a variable-speed characteristic, similar to that possessed by a continuous-current series motor, while its performance at starting is satisfactory.

The types of alternating-current commutator motors developed for electric traction are those possessing a variable-speed (series) characteristic, and include the compensated (or neutralised) series motor, the compensated-repulsion motor, the brush-shifting repulsion motor (Déri type), and the series-repulsion or "doubly-fed" motor.† All these motors are characterised by a laminated field structure (which, in the series motor, may have salient poles, but in motors of the repulsion type the polar face must be continuous) and an armature (or rotor) with a continuous-current winding, commutator, and brushes. This type of rotor, with commutator and brushes, is essential for obtaining the variable-speed characteristic, and the introduction of these features into alternate-current machines is accompanied by operating conditions which are non-existent with induction motors. Expressed briefly, these new conditions involve the problems of power-factor and commutation, of which the latter is considerably more complicated than the commutation problem in continuous-current machines. The means adopted for overcoming these difficulties will appear in the following discussion of the principles of the above types of motors.

* The single-phase induction motor has been applied to electric locomotives for the purpose of converting single-phase current into three-phase or continuous current. In the former case, the machine is provided with additional windings and acts as a phase converter, supplying three-phase current to the driving motors (see Chapter XVII). In the latter case, the motor forms part of a motor-generator set, which supplies continuous current to the driving motors. (See *The Electrician*, vol. 57, p. 850, for description of an experimental locomotive developed on this system.)

† Although all the above types of motors, including also the simple repulsion motor, are in service on the Continent, the present tendency is towards the standardisation of only the series and the series-repulsion types. (See article on "Electrification of Trunk Lines in Europe," R. E. Hellmund, *The Electric Journal*, vol. 10, p. 984.)

THE ALTERNATING-CURRENT SERIES MOTOR

Consider a series motor with a laminated magnetic circuit. If this motor is supplied with alternating current at low periodicity, the machine will be found to possess operating characteristics (neglecting commutation) similar to those of a continuous-current series motor,* the speed varying with the torque and the applied voltage in practically the same manner as if the motor were running with continuous current. The power-factor, however, will be very low, on account of the self-induction of the armature and field circuits.

The effect of the inductance of the motor on the power-factor is shown in the vector diagram of Fig. 33, in which OI represents the current, OV the terminal voltage, and ϕ the phase displacement between

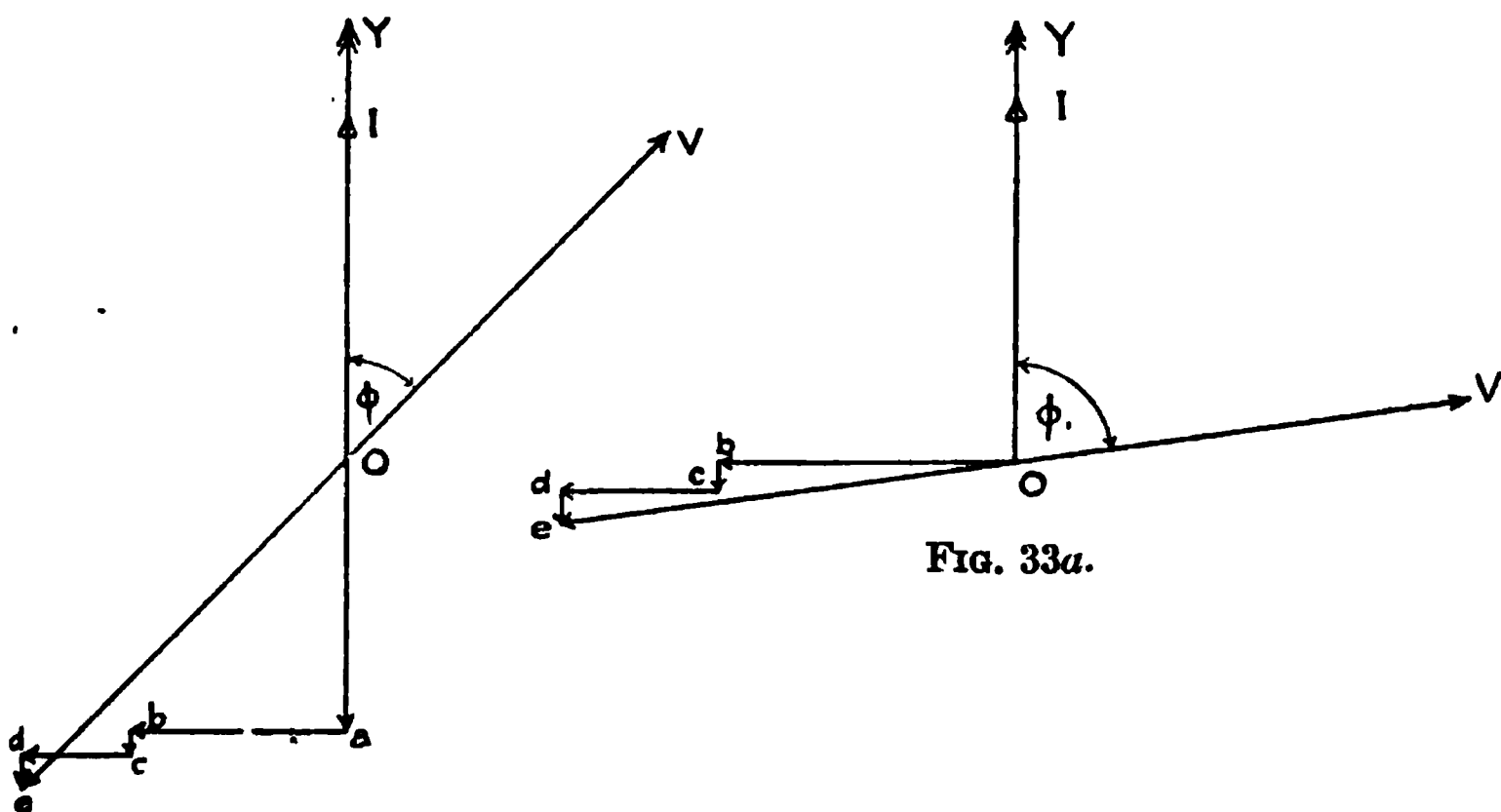


FIG. 33.

these quantities. The terminal voltage OV must be equal and opposite to the internal voltage of the motor: the latter is equal to the vector sum of (1) the E.M.F. generated in the armature by its rotation in the main field, and (2) the E.M.F.s due to inductance and resistance in the armature and field circuits. If we assume that the flux (OY) is in phase with the current, then the counter-E.M.F. generated in the armature can be represented by Oa —in phase opposition to OY —while the E.M.F.s due to resistance and inductance will be, respectively, in phase with Oa and at right angles thereto. These various E.M.F.s are represented by bc , de (the resistance drop in the armature and field circuits respectively), and ab , cd (the inductive drop in the armature and field circuits respectively). The internal voltage of the motor is therefore given by Oe .

The conditions at starting are represented in Fig. 33a, and in this case the power factor is nearly zero.

* The torque will, of course, be pulsating, and this will tend to produce excessive vibration at starting.

An inspection of Fig. 33 will show that the angle of lag (ϕ) is given by $\tan^{-1} \frac{ab+cd}{Oa+bc+de}$ (or $\frac{\text{wattless component of terminal voltage}}{\text{energy component of terminal voltage}}$). There-

fore, in order to improve the power-factor, we must reduce $(ab+cd)$ —which represents the total inductive voltage of the motor—and increase Oa , the dynamic E.M.F. generated in the armature. Now the inductive voltage in the field winding is caused by the main flux, and therefore this voltage cannot be neutralised,* although, by suitable design, it may be reduced to a value that is not objectionable. On the other hand, the inductive voltage in the armature winding is caused by the cross-flux due to armature reaction, which flux has a fixed position in space—according to the position of the brushes—and is not necessary for the production of the torque.† Therefore, this cross-flux may be neutralised, wholly or partially, by means of a suitable winding on the stator.

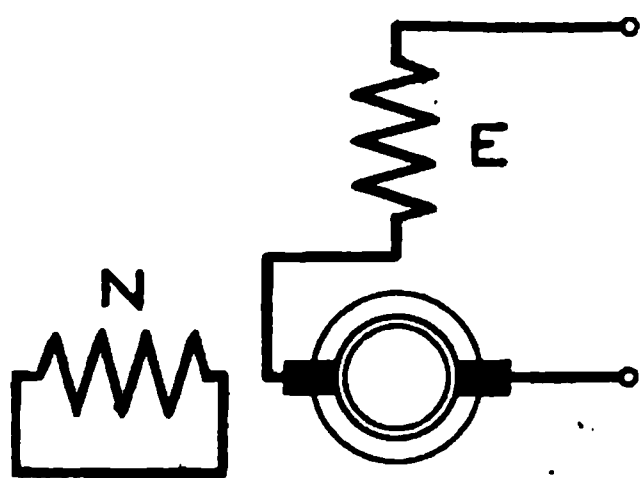


FIG. 34a.

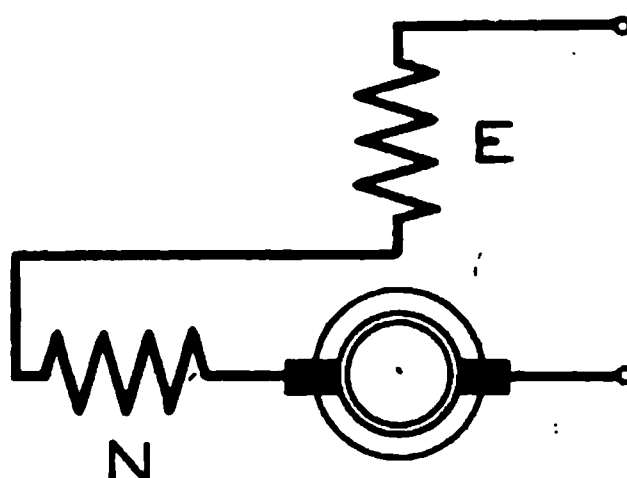


FIG. 34b.

For a complete neutralisation of the cross-flux, the neutralising (or compensating) winding on the stator must be distributed in the same manner as the armature winding, with the magnetic axis of the neutralising winding coincident with the magnetic axis of the armature winding, and the resultant ampere-turns along this axis must be zero. If the brushes are in the geometrical neutral position, the magnetic axis of the neutralising winding will be at right angles to that of the main field winding.

The neutralising, or compensating, winding may be either short-circuited upon itself—as represented in Fig. 34a—or connected in series with the armature and field windings, as represented in Fig. 34b.‡ With the former method (Fig. 34a) the machine is only partially compensated, as the ampere-turns of the compensating winding are derived from the armature through transformer action. The method, however, has the

* It is possible, by means of a special winding on the armature, to compensate the inductive voltage of the field winding by a dynamic voltage, and, with the armature reaction compensated, to obtain practically unity power-factor at all loads; but this method results in increased heating and reduced torque, and is, in consequence, not adopted in commercial machines. See *The Electrician*, vol. 58, p. 408.

† Moreover, the presence of the cross-flux in the neutral zone is detrimental to commutation.

‡ The machine of Fig. 34a is said to be “inductively compensated,” while the machine of Fig. 34b is said to be “conductively compensated.”

advantage that the number of turns do not require to be carefully chosen, and consequently a heavy bar winding can be adopted.

With the conductive, or "forced," compensating winding (Fig. 34*b*) any desired compensation can be obtained, and this method is largely used in practice. In some cases, however, it is not always practicable to obtain the correct number of turns for complete compensation. If the winding is suitably designed, there will be only a very small inductive voltage in the armature circuit, this voltage being caused by leakage between the teeth.

The power-factor of the compensated-series motor will, therefore, be considerably higher than that of the uncompensated motor, while, due to the absence of armature reaction, the commutation will be better. The improvement in the power-factor is shown in the vector diagram of Fig. 35, which should be compared with Fig. 33, the same letters being used in each diagram to represent the respective voltages.

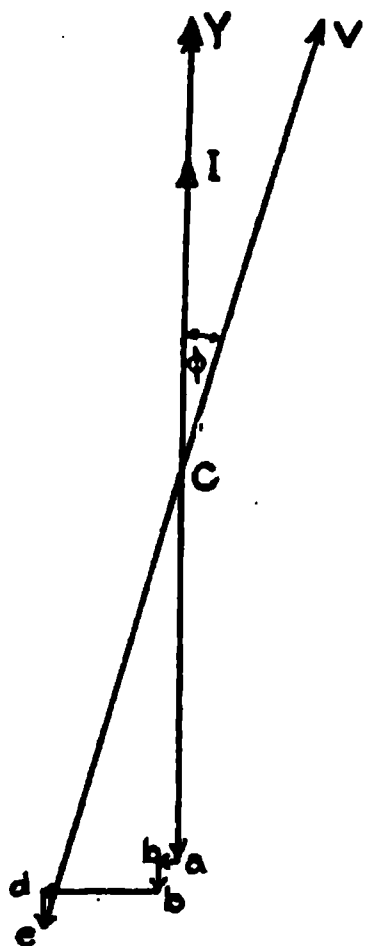


FIG. 35.

The power-factor may be still further improved by reducing the inductive voltage in the field winding, which may be accomplished by (1) supplying the motor with current at low frequency (15 cycles has been standardised on the Continent and 25 cycles in America), (2) adopting a small air-gap in conjunction with a low flux-density and an unsaturated magnetic circuit, (3) adopting a large number of poles and a low flux per pole. The adoption of a low flux per pole will require a corresponding increase in the number of armature turns in order to obtain the requisite torque. Consequently the ratio

$$\frac{\text{armature ampere-turns per pole}}{\text{field ampere-turns per pole}}$$

will be much greater than is customary with continuous-current motors. In compensated motors the armature ampere-turns are only limited by considerations of heating, but, in order to accommodate the increased ampere-turns, the diameter of the armature will have to be chosen larger than that of a continuous-current motor of equal rating.

If losses and magnetic leakage be neglected, the relation between the power-factor, armature turns, field turns, number of poles, speed and frequency is given by

$$\cos \phi (= \text{power-factor}) = \sqrt{\frac{1}{1 + (\frac{1}{2}\pi ab)^2}} \quad \dots \quad (14)^*$$

* This expression follows readily from Fig. 35 if losses and magnetic leakage be neglected. Thus,

$$\begin{aligned} \tan \phi &= \frac{\text{inductive voltage in field winding}}{\text{dynamic voltage generated in armature}} \\ &= \frac{\frac{2\pi}{\sqrt{2}} f \cdot T_f \cdot \Phi_m \times 10^{-2}}{\frac{4}{\sqrt{2}} f_1 \cdot T \cdot \Phi_m \times 10^{-2}}, \end{aligned}$$

where f is the frequency of supply, f_1 the frequency of rotation of the armature, T_f the total turns in the field winding, T the turns in series between the brushes,

where $a = \frac{\text{total field turns}}{\text{armature turns in series between brushes}},$

and $b = \frac{\text{synchronous speed in r.p.m.}}{\text{speed of rotation of armature in r.p.m.}}$

This expression shows that a high power-factor will only be obtained with small values for a and b .

Commutation.—The conditions which affect commutation are considerably more complicated than those met with in continuous-current motors, the principal difficulty being the “transformer voltage,” which is induced by the alternating flux in the coils undergoing commutation. It will be realised that, with the brushes in the neutral position, the coils undergoing commutation are in the position of maximum mutual inductance with respect to the main field winding, and consequently behave like the secondary winding of a transformer, of which the field winding forms the primary. Hence, if the armature coils, commutator connections, and brushes have only a low resistance and inductance, it follows that large circulating currents will be produced in the coils short-circuited by the brushes. These circulating currents are detrimental to the performance of the motor, for they lead to increased losses in the armature, and are the cause of excessive sparking at the brushes; moreover, they produce a reaction which results in a weakening of the main flux, as well as a phase displacement between this flux and the main current, thereby reducing the torque.

The reaction produced by the circulating currents is represented in the vector diagram of Fig. 36, in which OY represents the main flux, OB the ampere-turns to produce this flux, and OF the transformer voltage, which, of course, is in time quadrature with the flux. If we assume the inductance of the short-circuited coils to be negligible, and disregard any other E.M.Fs. that may be induced in these coils, then the circulating currents produced by the transformer voltage can be represented by OG , in phase with OF . The reaction ampere-turns, due to the circulating currents, are represented by OC , and act along the axis of the field winding in opposition to the field ampere-turns. Therefore, OB must represent the resultant of the field ampere-turns and the reaction ampere-turns. Hence the field ampere-turns are represented by OA , and the main current by OI , which leads the flux by the angle θ , thereby reducing the angle ϕ (Fig. 35) and improving the power-factor.

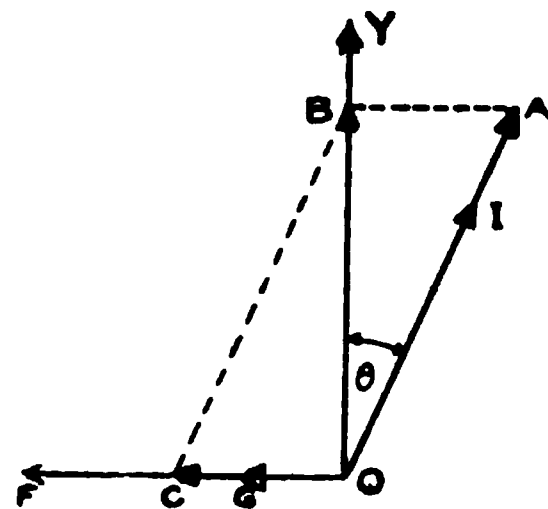


FIG. 36.

The improvement in the power-factor, however, is accompanied by

and Φ_m the crest value of the flux, the distribution of which is assumed to be sinusoidal. Hence

$$\tan \phi = \frac{\pi}{2} \cdot \frac{f}{f_1} \cdot \frac{T_f}{T} = \frac{\pi}{2} \cdot \frac{n_s}{n} \cdot \frac{T_f}{T} = \frac{\pi}{2} a \cdot b$$

(n_s = synchronous speed in r.p.m. n = armature speed in r.p.m.)

Whence

$$\cos \phi = \frac{1}{\sqrt{1 + \tan^2 \phi}} = \frac{1}{\sqrt{1 + \left(\frac{\pi}{2} ab\right)^2}}$$

a reduction in the torque, since the latter is represented by the product $OY \times OI \cos \theta$.

Thus the circulating currents lead to (1) a reduction of the output, (2) an increase in the losses, (3) a reduced efficiency, and (4) an improvement in the power-factor. As it is obviously undesirable to improve the power-factor at the expense of the efficiency and thermal constants of the motor, features must be incorporated into the design to reduce the circulating currents to a minimum.

First let us consider, briefly, what steps must be taken in order to *neutralise* the transformer voltage. Since this voltage is produced by induction from the main flux, therefore it can only be neutralised by a *dynamic E.M.F.*, which must be generated in the commutated coils by their rotation in a commutating flux of the correct flux-density and phase. Moreover, as the transformer voltage has a phase displacement of 90 degrees (lagging) in relation to the main flux, the commutating poles must have shunt excitation. Generally, a compound (series and shunt) excitation must be adopted, as discussed below, in order to compensate the reactance voltage, but complete neutralisation of the transformer voltage can only occur over a limited range of speeds.

Whatever methods are adopted for neutralising the transformer voltage when the armature is rotating, these methods are of no use under starting conditions, and therefore other features must be introduced into the design of the motor.

Now the magnitude of the circulating currents at starting can be reduced by (1) reducing the magnitude of the transformer voltage, (2) increasing the resistance of the path of the circulating currents.

Since the static E.M.F. (e_s) induced in a coil of t turns by the alternations of a flux Φ_m is given by

$$e_s = 4.44 t f \Phi_m \times 10^{-2},$$

therefore, if m coils are short-circuited by a brush, the transformer voltage (e_t) causing circulating currents in these coils will be given by

$$e_t = 4.44 m t f \Phi_m \times 10^{-2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

Hence e_t can be reduced by (a) reducing the number of coils short-circuited by a brush, (b) reducing the number of turns per armature coil to the minimum value (viz. unity), (c) adopting a low flux and a low frequency.

The resistance of the path of the circulating currents may be increased by (d) the use of high-resistance brushes and (e) the introduction of "resistance leads" or high-resistance connections between the armature coils and the commutator segments,* as indicated diagrammatically in Fig. 37.

The **resistance connections** usually consist of a high-resistance alloy (such as rheostan or "Eureka"), and connect the junctions of the armature coils to the commutator segments (see Fig. 37), the connections being generally located in the slots with the armature winding as described below (page 92). On account of considerations of space, and as the leads are not carrying current continuously, it is the practice to design them for a high current density (about 1500 to 2000 amperes per square inch).

* These resistance connections can be arranged as active conductors to add to the torque (see p. 94).

The number of coils short-circuited by a brush can be reduced by means of a duplex armature winding * or (which is more usual) the use of narrow brushes covering not more than two segments. These brushes are generally of high resistance so as to conform to condition (d).

The reduction of the armature turns per coil to unity introduces a limitation to the armature voltage, since, with a multiple-circuit armature winding and a large number of poles, the number of segments per pole (and therefore the turns per circuit and the voltage) are limited by the largest permissible diameter of commutator and the narrowest width of segment.†

Hence we usually find alternating-current series motors, of moderate outputs, built for voltages of from 200 to 300 volts, although, under favourable conditions, voltages up to 450 volts have been adopted for motors of large outputs. In the latter cases, satisfactory operation has

Armature Winding.

Resistance Connections.

Commutator Segments.

FIG. 37.

been obtained without the use of resistance connections. With machines of small and moderate outputs, in which a high torque must be developed at starting and where considerations of space do not allow the most favourable conditions to be adopted in the design, it is practically impossible to obtain satisfactory operation unless resistance connections are used.

In our consideration of the power-factor we found that a low flux and a low frequency were desirable, and we now find that these conditions must be satisfied in order to obtain satisfactory commutation. In fact, it is due to adoption of the low frequency of 15 cycles that the alternating-current series motor has been developed to its present state of perfection in large machines. This brings us to the consideration of the conditions which limit the output of a single-phase series motor.

If we neglect friction, windage, and core losses, the output of the

* A duplex armature winding consists of two re-entrant windings, the commutator segments being connected alternately to conductors in each winding. (See *Electric Motors*, Hobart, p. 50.)

† Moreover, the minimum width of segment must be chosen with reference to the minimum practicable thickness for the brushes.

phase motors these formulæ have to be modified to take into account the difference in the operating conditions * in the two cases and the difference in the armature construction, since, generally, single-phase armatures are constructed with partially closed slots.

The "reactance voltage" is approximately in phase with the armature current, while its magnitude depends on the current, the speed, and other factors concerned with the design.

The "rotation voltage" is in phase with the armature cross-flux, which is in phase with the armature current.

The reactance and rotation voltages are, therefore, out of phase with the transformer voltage; hence the vector sum of these three voltages must be considered in obtaining the resultant circulating current.

When the machine is provided with commutating poles, the portion (if any) of armature cross-flux which is not neutralised by the compensating winding must be neutralised by an equal flux from the commutating

FIG. 38.

poles before a commutating flux can be established. Under these conditions we have only to consider the resultant of the transformer and reactance voltages in determining the commutating voltage to be generated in the short-circuited coils by their rotation in the commutating flux.

The methods adopted for exciting the commutating poles, in order to obtain the correct phase of the commutating flux, are (1) compound winding (in conjunction with commutating poles of special design), (2) series winding shunted with non-inductive resistance, (3) shunt winding in series with a transformer connected across the main field winding.

Method (1) has been developed and perfected by the **Siemens' Companies**, and is indicated diagrammatically in Fig. 38. The commutating pole consists of three teeth. Around the central tooth is wound the series winding, the ampere-turns of which must neutralise the uncompensated armature ampere-turns and provide the component of the commutating flux to compensate the reactance voltage. The shunt winding surrounds the whole of the pole, and provides the component of the commutating flux to compensate the transformer voltage.

* Generally, with single-phase motors, the instantaneous value of the armature current (for a given armature coil) at the commencement of the commutation period differs from that at the end of this period. The difference in these instantaneous values of the armature current depends on the ratio between the frequency of the supply current and the frequency of commutation.

This arrangement of the windings is necessary in order to reduce the inductive action between the series and shunt coils. With the arrangement shown in Fig. 38 the shunt current is only affected very slightly by the current in the series coil.

Vector Diagram for compound-wound commutating poles.—The method of obtaining the correct proportion of shunt and series turns is shown in the vector diagram of Fig. 39, which represents the conditions for perfect commutation (i.e. no circulating currents) at a certain load and speed. The main flux (OY) will, therefore, be in phase with the main current OI , thus giving a phase displacement of 90 degrees between the transformer and reactance voltages, which are represented by Ox and Oy respectively. The commutating flux must be of such magnitude and phase that a voltage (Or) equal and opposite to Oz —the resultant of Ox and Oy —is generated in the coils undergoing commutation. This flux is represented by OZ .

The ampere-turn diagram, corresponding to the voltage diagram of Fig. 39, is shown in Fig. 40, in which OA represents the field ampere-turns producing the main flux OY , while Oq (of the same phase as OZ

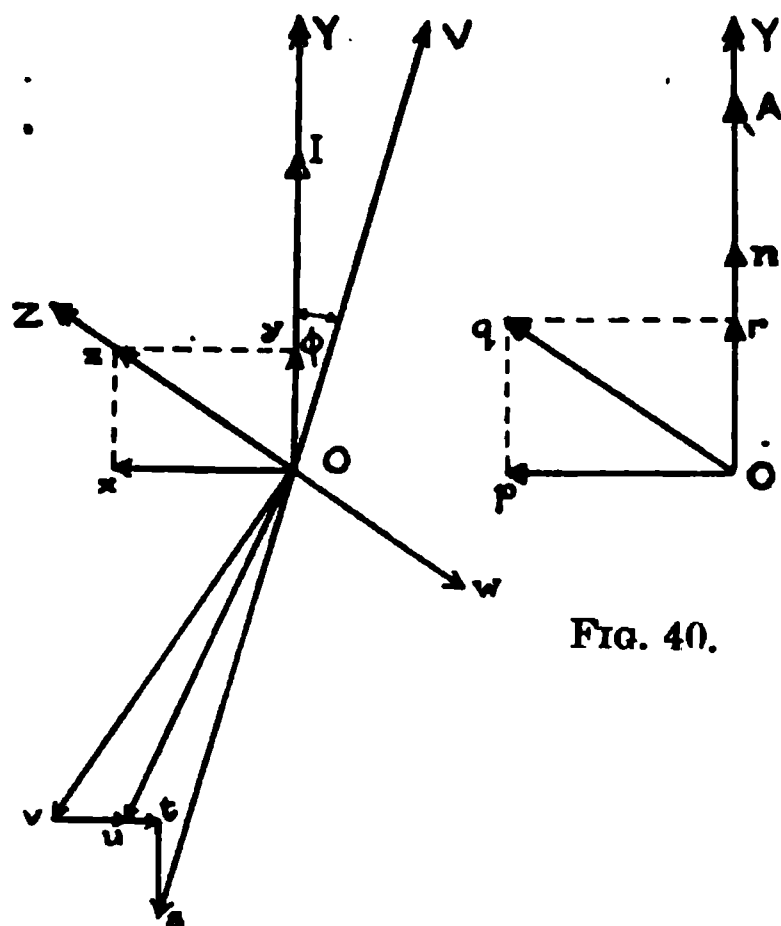


FIG. 40.

FIG. 39.

in Fig. 39) represents the ampere-turns required for the production of the commutating flux, and Or , Op the components of these ampere-turns supplied by the series and shunt windings respectively. The total series ampere-turns on the commutating pole will generally be greater than Or by an amount sufficient to neutralise the uncompensated armature turns. If the latter are represented by rn , then On will represent the total series ampere-turns to be provided.

It now remains to determine the magnitude and phase of the voltage to be applied to the shunt winding in order that the shunt current shall be in phase with Op . Referring to Fig. 39, the E.M.F. induced in the shunt winding by the com-

mutating flux is represented by Ov (at right angles to OZ), while the voltage drop due to the resistance of the winding is represented by vu . Therefore a voltage equal and opposite to Ov must be applied to the terminals of the shunt winding. Now this voltage will generally differ in magnitude and phase from the terminal voltage (OV) of the motor, so that it will be necessary to add resistance or reactance (or both) to the shunt circuit before the correct shunt current can be obtained. In the case under consideration, an impedance coil, having a resistance drop equal to ut and a reactance drop equal to ts , must be connected in series with the shunt winding.* The total voltage in the shunt circuit

* In some cases a small transformer, or a tapping on the main transformer, is used for supplying the voltage to the shunt winding, and under these conditions only an adjusting resistance will be required.

will then be represented by Os , which is equal and opposite to the impressed voltage OV .

A series-wound commutating pole, shunted with a non-inductive resistance, has been standardised by the Oerlikon Co. for their single-phase series motors. The connections are indicated in Fig. 41, while in Fig. 42 is given a vector diagram, which shows how the desired phase of the commutating flux is obtained. In this diagram (which represents the conditions for ideal commutation) the magnitude and phase of the ampere-turns required to produce the commutating flux OZ is represented by Oq , while OY represents the main flux and OI the main current. If the armature ampere-turns are completely compensated, then the ampere-turns on the commutating pole must be equal to Oq . The current in the commutating-pole winding must be in phase with Oq ; and if OH represents the current required, then OK —the vector difference of OI and OH —represents the current in the shunt resistance.

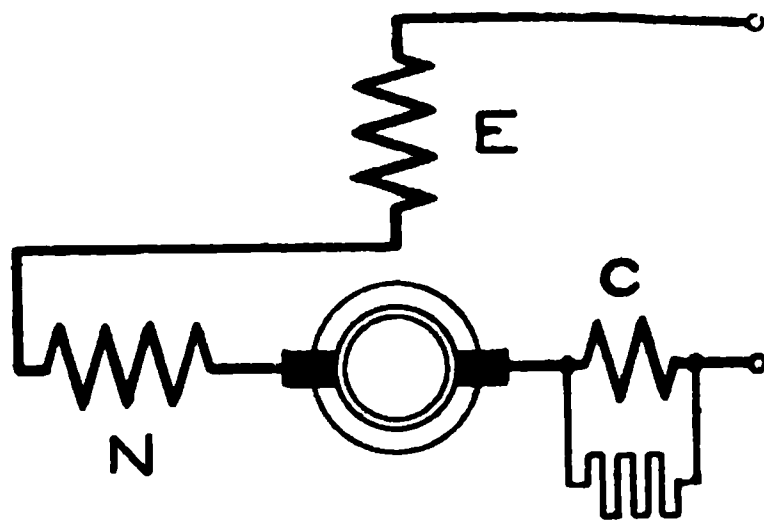


FIG. 41.

The voltage drop Ou in the commutating-pole circuit is obtained by compounding Ov (which represents the E.M.F. induced in the commutating-pole winding) with vu (which represents the resistance drop in the winding). The value of the shunt resistance is then obtained by dividing Ou by the shunt current OK .

The results obtained by this method of excitation have been quite satisfactory, and, with high-speed 15-cycle motors, the losses in the shunt resistance are only of the order of $\frac{1}{4}$ to $\frac{1}{3}$ of 1 per cent.* of the output of the motor. With low-speed 25-cycle motors, however, the loss in the shunt resistance would generally be of such a magnitude to render this system of excitation impracticable.†

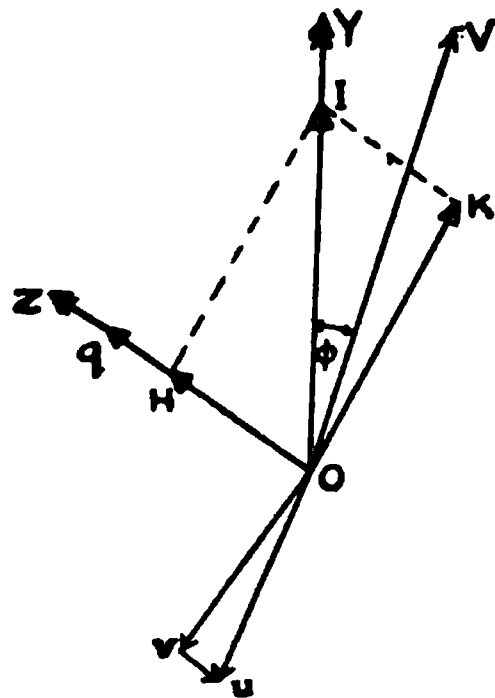


FIG. 42.

The application of a **shunt-wound commutating pole**, in conjunction with a booster-transformer excited from the field winding of the motor, is indicated in the connection diagram of Fig. 43. This method—devised by Latour—has been used by Messrs. Siemens-Schuckert ‡ in addition to the compound-wound commutating pole described above.

The vector diagram for this method of exciting the commutating poles is rather complicated, on account of the large number of quantities which have to be considered, so that, to simplify matters, we shall assume that (1) the armature ampere-turns are completely compensated, (2) the

* See a paper on "Single-phase Traction," by Marius Latour (*Journal of the Institution of Electrical Engineers*, vol. 51, p. 518.) An investigation of the losses with the above method of excitation is given in the paper (pp. 514–518).

† See *The Electric Journal*, vol. 10, p. 989.

‡ *The Electrician*, vol. 58, p. 250.

commutation is perfect (*i.e.* there are no circulating currents), (3) the losses and leakage in the booster-transformer are negligible. The ampere-turns on the commutating pole will, therefore, only have to provide the commutating flux.

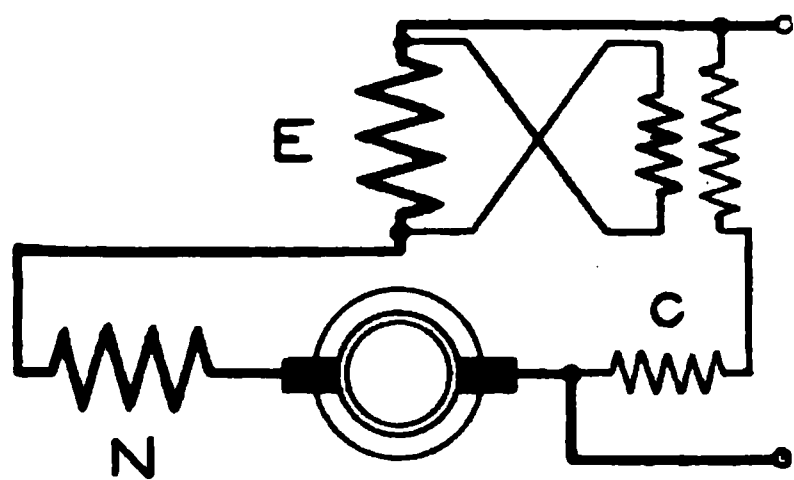


FIG. 43.

A consideration of Fig. 43 will lead to the following deductions: (1) the impressed voltage on the primary of the booster-transformer is equal to the voltage impressed on the field winding; (2) the armature current differs in magnitude and phase from the field current; (3) the current in the secondary of the booster-transformer is equal to the current in the commutating-pole winding; (4) the vector sum of

the voltages across the commutating-pole winding and the secondary of the booster-transformer must equal the line voltage (in phase and magnitude).

In order to render the vector diagram legible, it has been drawn in two portions—one (Fig. 44a) relating generally to the various currents, and the other (Fig. 44b) relating to the various E.M.F.s.

Referring to Fig. 44b, OY represents the main flux, while Of , fg represent respectively the inductive and resistance drops in the field winding (Of is at right angles to OY , and fg is parallel to the field current

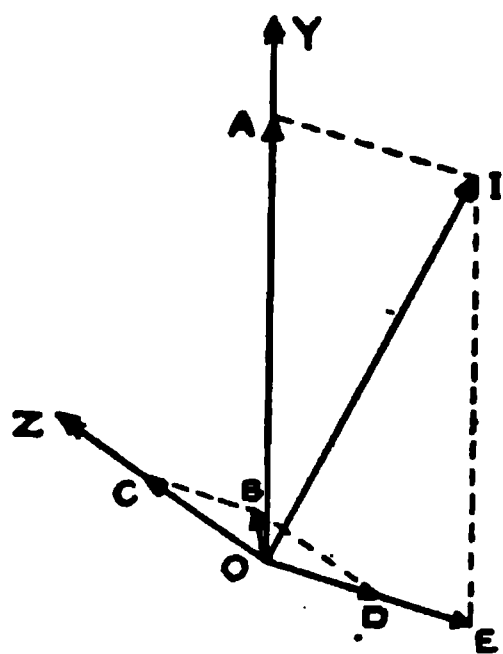


FIG. 44a.

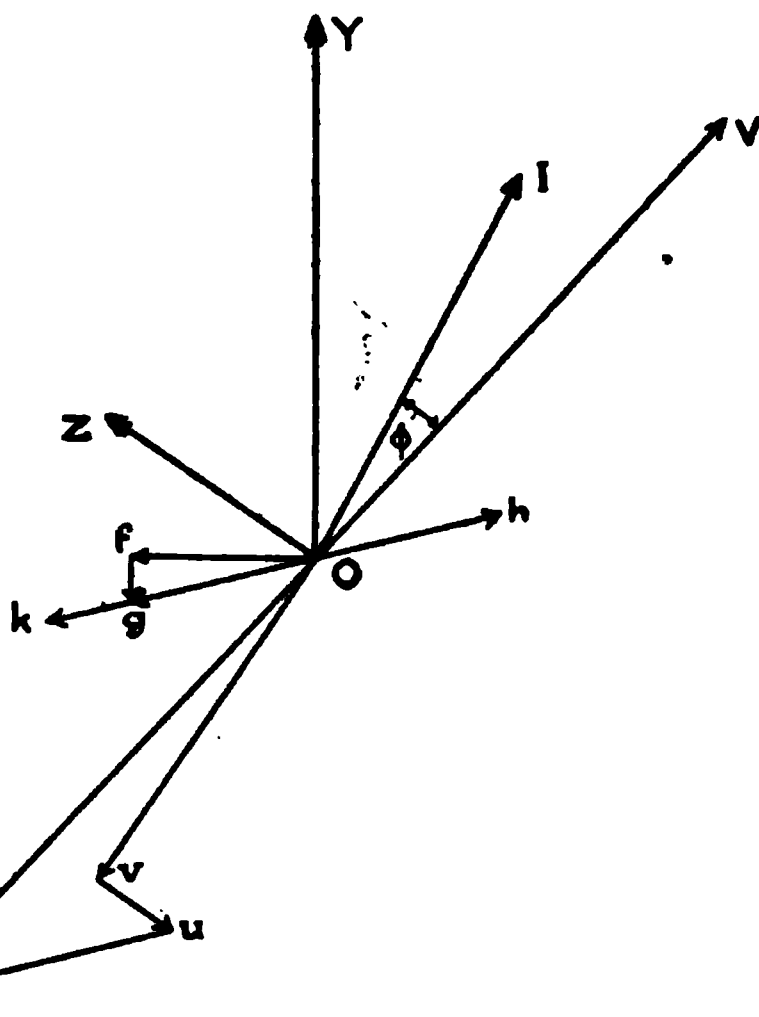


FIG. 44b.

OA (Fig. 44a)). The impressed voltage on the field winding and the primary of the booster-transformer is, therefore, represented by Oh (equal and opposite to Og), while the secondary E.M.F. of the transformer is represented by Ok (equal to $Oh \times$ ratio of transformation).

Referring to Fig. 44a, OA represents the field current, in phase

with the flux OY ; OC the current in the commutating-pole winding, in phase with the commutating flux OZ * (Fig. 44b); OB the magnetising current of the booster-transformer, at right angles to Oh (Fig. 44b); $OD (=OC - OB)$ the current in the primary of this transformer, assuming a 1:1 ratio of transformation; OE the actual primary current; and $OI (=OA + OE)$ the armature current.

Referring again to Fig. 44b, the line voltage is represented by OV , while Os —equal and opposite to OV —represents the sum of the voltages in the shunt circuit. The voltage induced in the commutating-pole winding by the commutating flux OZ is represented by Ov —at right angles to OZ —and the resistance drop in this winding is represented by vu . Hence, us —equal and parallel to Ok —must close this voltage polygon, otherwise an adjusting resistance or a choking coil will be required (see remarks in connection with Fig. 39).

Vector Diagram for the ideal series motor.—The vector diagram for an ideal motor is given in Fig. 45, which is a simplification of

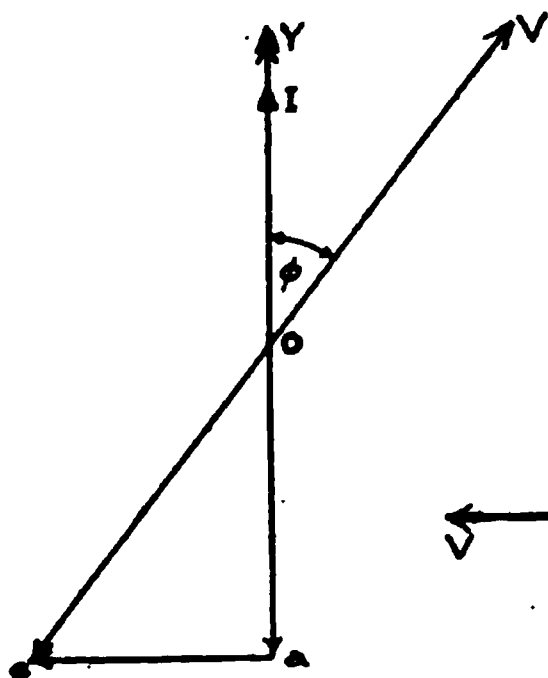


FIG. 45.

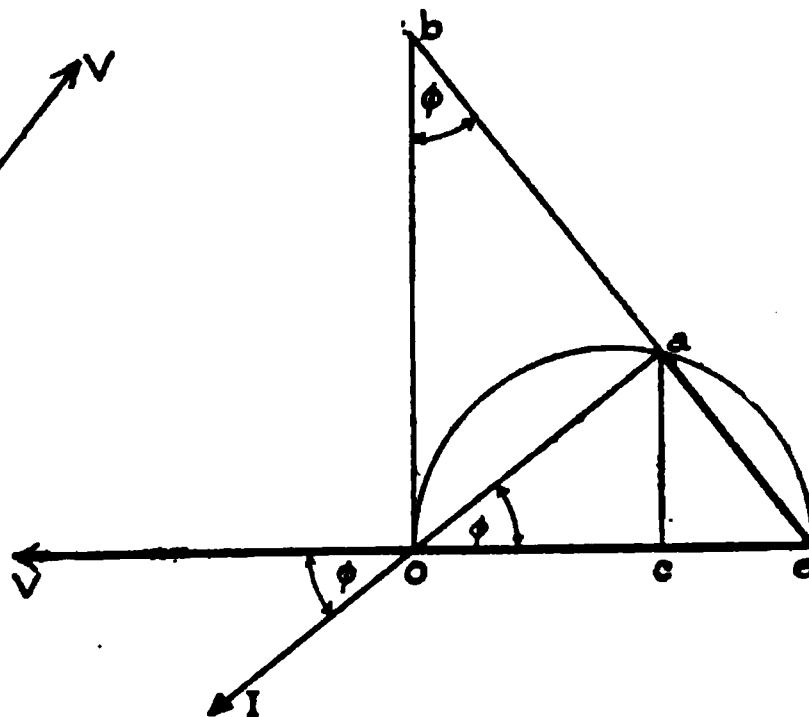


FIG. 46.

Fig. 33 (p. 52). Referring to Fig. 45, OY represents the flux, OI the current, OV the terminal voltage, and Oe the total internal voltage (equal and opposite to OV) which is compounded from (1) the counter-E.M.F. generated in the armature (represented by Oa), and (2) the E.M.F. of self-induction (represented by ae). If we regard Oe to be fixed in position and constant in magnitude, then, when the load (or current) is varied, the point a will describe a semicircle, of which Oe is the diameter (see Fig. 46). If we neglect saturation of the magnetic circuit, then this diagram (Fig. 46) enables us to obtain the complete performance of the motor.

Now the power-factor is given by $\cos \phi$, or Oa/Oe . Hence, as Oe is constant, *the length of Oa will be proportional to the power factor.*

The inductive voltage in the motor is represented by ea , and as the inductance is constant, *the length of ea will be proportional to the current.*

Since the counter-E.M.F. generated in the armature is proportional to the product of the flux and the speed, and the flux is proportional

* It is necessary to assume the magnitude and phase of the reactance voltage before the commutating flux can be obtained.

to the current, therefore Oa will be proportional to (current \times speed). Hence the speed will be proportional to the ratio Oa/ea . If a perpendicular be erected on Oe at O , and ea be produced to cut it at b , then $Oa/ea = Ob/Oe$. Hence *the length of Ob will be proportional to the speed.*

From a drop the perpendicular ac on to Oe . Then ac will represent *the watts input and also the watts output.**

The *maximum output* will be given by the maximum value of ac , which is equal to $\frac{1}{2}Oe$.

If point a corresponds to full load, then the *overload capacity* (ξ) will be given by

$$\xi = \frac{\frac{1}{2}Oe}{ac} = \frac{\frac{1}{2}Oe}{\frac{ae \times Oa}{Oe}} = \frac{\frac{1}{2}}{\frac{ae}{Oe} \times \frac{Oa}{Oe}} = \frac{1}{2 \sin \phi \cos \phi} = \frac{1}{2 \cos \phi \sqrt{1 - \cos^2 \phi}}.$$

[NOTE.— $\cos \phi$ here refers to the full-load power-factor.]

The torque is proportional to (current \times flux) or (current)², i.e., ea^2 . Now $ea^2 = Oe \times ce$. Hence *the length of ce will be proportional to the torque.*

If the ratio $\frac{\text{stand still current}}{\text{full load current}} \left(= \frac{Oe}{ae} \right)$ be represented by σ , then

$1/\sigma = \sin \phi$, and the power-factor at full load will be given by

$$\cos \phi = \sqrt{1 - \sin^2 \phi} = \sqrt{1 - \frac{1}{\sigma^2}}.$$

Summarising we have,

Oa	is proportional to the power-factor,
ea	current,
Ob	speed,
ac	watts input and watts output,
ce	torque.

We are thus able to predetermine the complete performance curves of the motor.

In commercial motors, however, the conditions are not ideal, for we have losses, magnetic saturation, magnetic leakage, and circulating currents, the latter producing a reaction which results in a phase displacement between the current and the flux. Now all these items vary with the load, so that, if we wish to predetermine the performance curves of a commercial motor, we must construct a vector diagram for each load and voltage. This vector diagram will really be a combination of the vector diagrams already given. The process, however, is not straightforward, as it is necessary to assume the magnitude and phase of some of the quantities before the diagram can be completed. We shall, therefore, discuss the diagram in detail.

Vector Diagram for the Compensated Series Motor with Commutating Poles.—As an example of the method to be adopted in a particular case, we will consider that the performance curves are required for

* The watts input = volts \times current $\times \cos \phi = Oe \times ae \times \cos \phi$
 $= Oe \times ae \times Oa$
 $= Oe \times 2(Oe \times \frac{1}{2} ac)$
 $= Oe^2 \times ac.$

a commutating-pole compensated series motor for which the full design data are available. If we only require the performance curves for one operating voltage, then we must assume a range of values for the flux, and obtain the current and speed from the vector diagram by a process of trial and error. If, however, the performance curves are required for a number of voltages, then it is preferable to assume values for the flux and speed and determine the current from the diagram. A set of curves is then constructed giving the volt-ampere characteristics at definite speeds, from which the speed-current curve for constant terminal voltage can be obtained. In the present case, we will suppose that the performance curves are required for only one voltage.

A value is assumed for the main flux (OY , Fig. 47a). The saturation ampere-turns required for this flux are represented by OB . The re-

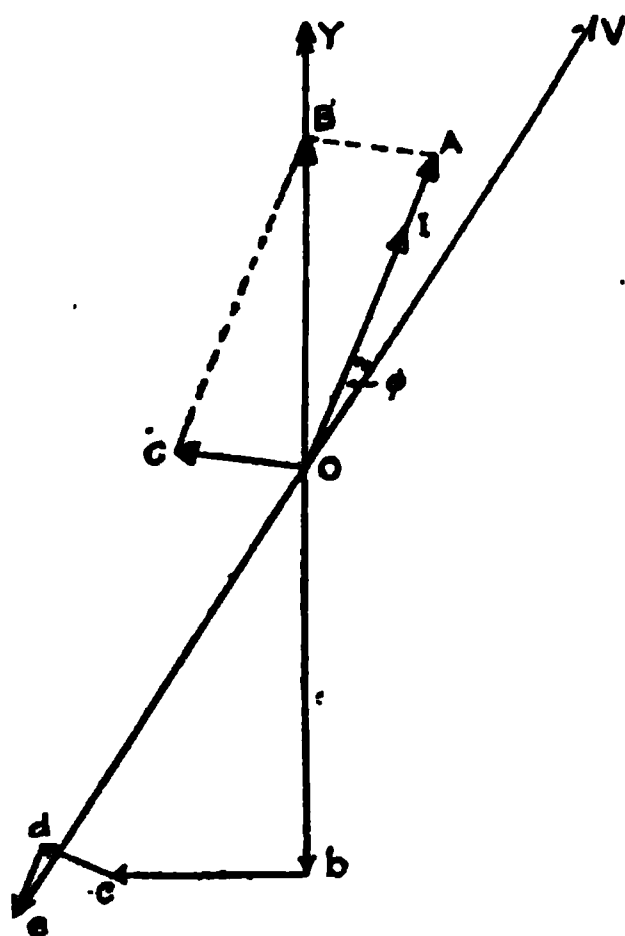


FIG. 47a.

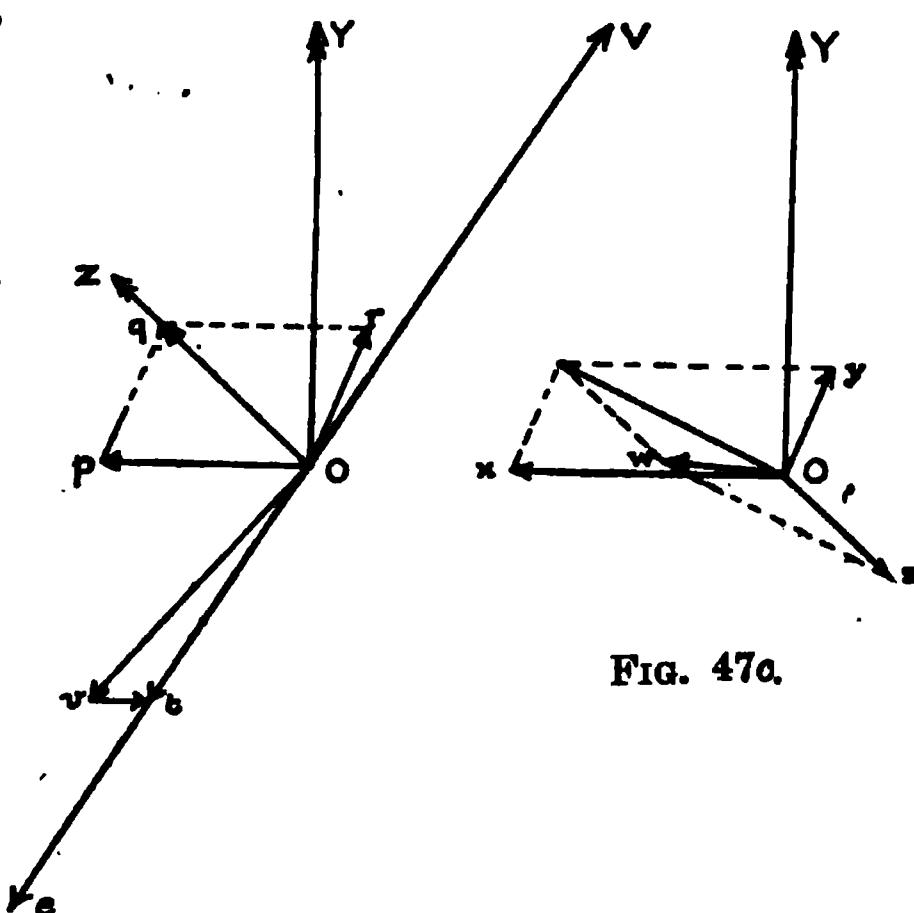


FIG. 47b.

action ampere-turns OC (due to circulating currents) must now be assumed—in magnitude and phase—in order that the field ampere-turns OA and the main current OI may be determined. If the power-factor is also assumed, we are able to construct the voltage part of the diagram and obtain the speed. Thus, in Fig. 47a, OV represents the terminal voltage, Oe (equal and opposite to OV) the total internal voltage, de (parallel to OI) the total resistance drop, cd (at right angles to OI) the reactance drop in the armature and compensating winding, bc (at right angles to OY) the inductive voltage in the field winding, and Ob the counter-E.M.F. generated in the armature by its rotation in the main flux. (NOTE.—The point b must lie on YO produced.) The speed can readily be obtained from the value of Ob and the flux.

We have now to check the magnitude and phase of the reaction ampere-turns OC . Now the voltage producing the circulating currents is the resultant of (1) the transformer voltage, (2) the reactance voltage, and (3) the commutating voltage, the latter being generated in the commutated coils by their rotation in the commutating flux. The transformer and the reactance voltages can be calculated, since the flux and current are known. The commutating voltage can also be

calculated by assuming the magnitude of the commutating flux. The phase and magnitude of this flux can be determined by a process of trial and error as follows:

Referring to Fig. 47*b*, let Oq represent the ampere-turns producing the commutating flux OZ , Or the resultant ampere-turns of the series winding, and $Op (=Oq - Or)$ the ampere-turns of the shunt winding. The shunt current and the E.M.F.s. in the shunt circuit can then be obtained. (See remarks in connection with Fig. 39, p. 60.) The total voltage in the shunt circuit, however, must agree—in magnitude and phase—with the line voltage, or a definite fraction thereof. The correct conditions are represented in Fig. 47*b*, in which Ov (at right angles to OZ) represents the inductive voltage in the shunt winding, vt (parallel to Op) the total resistance drop in the shunt circuit, and Ot (in phase with Oe) the total voltage in the shunt circuit.

Having obtained the magnitude and phase of the commutating flux, we are able to obtain the resultant (or circulating) voltage in the short-circuited coils. Thus, in Fig. 47*c*, Oy represents the reactance voltage, Ox the transformer voltage, Oz the commutating voltage, and Ow the resultant voltage. The circulating currents may be considered to be in phase with Ow , and the ampere-turns due to these currents are represented by OC , which must agree with the assumed value.

THE REPULSION MOTOR

Before discussing the compensated-repulsion motor, the Déri brush-shifting repulsion motor, and the series-repulsion motor, it will be desirable to investigate the principles and characteristic features of the simple repulsion motor.

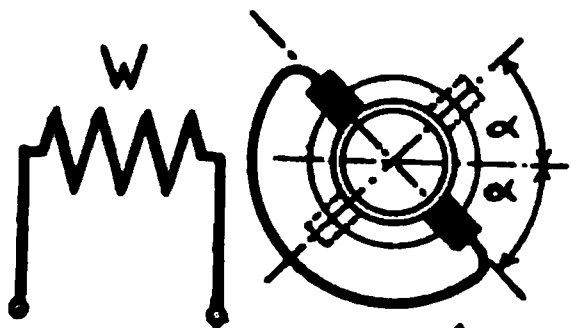


FIG. 48.

The simplest form of repulsion motor consists of a stator with a single-phase winding (which is distributed in the same manner as the winding of a single-phase induction motor), and a continuous-current armature with short-circuited brushes, the axis of the brushes being displaced from the magnetic axis of the stator winding, as indicated in Fig. 48.

The short-circuited brushes form the distinguishing feature of all types of repulsion motors, and fulfil an important function in the operation of these machines. Thus all repulsion motors are characterised by good commutation at synchronous speed (due to the resultant field being of a revolving nature, as in polyphase motors); but this feature also introduces serious limitations into the design of these motors for high-speed service on low-frequency systems.

In discussing the principles of the repulsion motor, it will simplify matters if we consider that the single stator winding W , of Fig. 48, consists of two windings T , E (Fig. 49), with their axes at right angles to each other, the axis of winding T being coincident with the magnetic axis of the armature, as indicated in Fig. 49.

This arrangement of the windings is adopted in practice for reversible motors, since, with a single stator winding, the direction of rotation can only be reversed by moving the brushes to the dotted position in Fig. 48.

The resultant ampere-turns of the two windings T, E, must be equal to the ampere-turns of the single stator winding W (Fig. 48).

Thus, if T_s denotes the turns in the single stator winding W (Fig. 48), T_s , T_e respectively denote the turns in the windings T, E (Fig. 49), and α denotes the angular displacement of the brushes from the axis of the stator winding (see Fig. 48), then $T_e = T_s \cos \alpha$, $T_e = T_s \sin \alpha$.

Now the winding T (Fig. 49) and the short-circuited armature winding form a transformer, and therefore electrical energy can be supplied to the armature (from winding T) by induction. Hence the axis of this winding is called the “energy” or “transformer” axis of the motor. On the other hand, winding E has no transformer action on the armature winding, and cannot transmit energy to the latter, but it provides the ampere-turns for the “field” or “excitation” flux. The axis of this winding is therefore called the “excitation” axis of the motor.

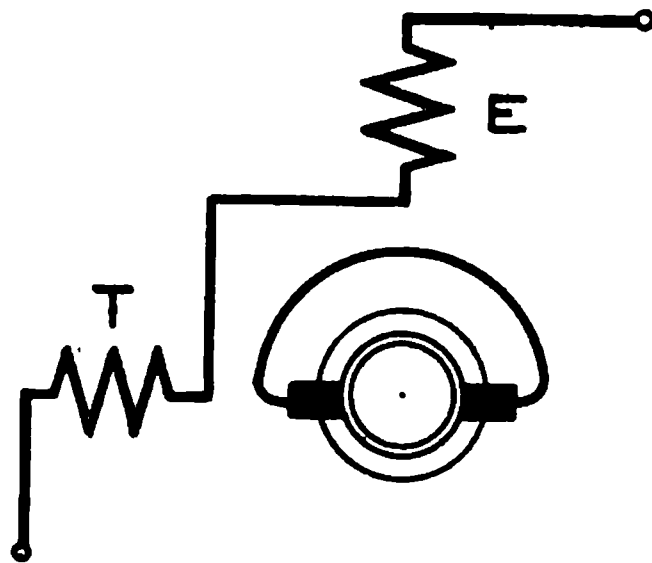


FIG. 49.

Starting conditions.—If we neglect magnetic leakage and losses, then, when a voltage is impressed on the stator windings with the armature stationary, the resultant ampere-turns along the energy axis must be zero.* Consequently the only flux in the machine is produced by the ampere-turns of winding E. Hence the whole of the supply voltage is consumed in this winding, and the current is entirely wattless.

The **phase relations** are shown in Fig. 50, where OI represents the stator current; OA , OB the ampere-turns of the stator windings E, T respectively; OC (equal to and opposite to OB) the armature ampere-turns; OY the flux produced by the resultant ampere-turns OA ; Od —at right angles to OY —the inductive voltage in the stator winding E; and OV (equal and opposite to Od) the terminal voltage.

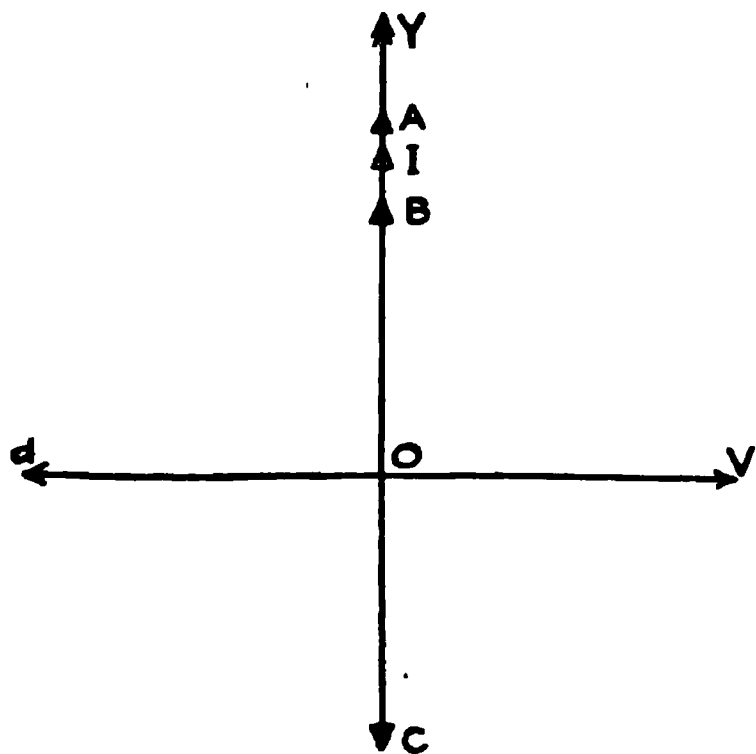


FIG. 50.

As the flux is in the direction of the excitation axis, a torque will be produced due to the interaction of the armature current and this flux, since the two latter are in time-phase. The torque will vary with the inclination of the brush axis (angle α in Fig. 48), and will be zero for two brush positions, viz. when the brushes are in line with the axis of the stator winding ($\alpha=0^\circ$), and when the brushes are displaced 90 degrees from this position ($\alpha=90^\circ$).

The magnitude of the circulating currents in the coils short-circuited

* The armature winding may be regarded as a compensating winding to the winding T, and, if resistance and leakage be neglected, there cannot be any resultant flux along the energy axis when the armature is stationary.

by the brushes will vary with the position of the brushes (assuming a single stator winding as in Fig. 48). Thus, when the brush axis is at right angles to the axis of the stator winding, the circulating currents are a maximum, but the armature (and stator) current is a minimum; while, when the axis of the brushes coincides with the axis of the stator winding, there are no circulating currents, but the armature (and stator) current is a maximum. This point is important in connection with speed control by brush displacement.

Running conditions.—Let us now consider the armature to be running and doing work. As we are neglecting losses, the work done by the armature must equal the energy supplied to the motor. It follows, therefore, that an E.M.F. must be induced in the stator-winding, in phase-opposition to the current, and that this E.M.F. must be overcome by a component of the supply voltage—in phase with the current—so that the product of the current and the component of the supply voltage in phase with it shall represent the power developed by the armature.

Now the electrical energy supplied to the stator must be transferred to the armature in order to be converted into mechanical energy, and this transference of energy can only take place through transformer action along the energy axis of the motor, *i.e., the mechanical energy developed by the armature must be supplied to it as electrical energy from the stator winding T*. A transformer flux must, therefore, be produced along the energy axis of the motor; and since the E.M.F. induced in the winding T is due to this flux, it follows that the latter must have a phase-difference of 90 degrees from the supply current; or, in other words, *the flux along the energy axis must have a phase-difference of 90 degrees from the flux along the excitation axis*. Moreover, these fluxes are 90 degrees apart in space. Hence it follows that the resultant flux in the motor is a *rotary flux*, and if the magnitudes of the two components of this flux are equal, then the motor will possess a *uniformly rotating field*, exactly similar to that in a two-phase induction motor; while, if the two components of the resultant flux are not equal in magnitude, then the motor will possess an *elliptical field*.

Now, since energy is transmitted from the stator to the armature by induction, it follows that a transformer (or static) E.M.F. must be induced in the armature winding by the component of the flux along the energy axis, while the product of this E.M.F. and the component of the armature current in phase with it must equal the power supplied to the armature.

Consider for the moment the E.M.Fs. in the armature. The static E.M.F. will have a phase-difference of 90 degrees from the flux which produces it, and will be in phase with the counter-E.M.F. induced, by this flux, in the stator winding T. Hence the static E.M.F. will be in (time) phase-opposition with the excitation flux. But by the rotation of the armature in the excitation flux, a dynamic E.M.F. is generated in the armature winding, and this E.M.F. is in (time) phase with the excitation flux. Therefore the static and the dynamic E.M.Fs. oppose each other. The difference between these E.M.Fs. (*i.e.* the resultant E.M.F. in the armature circuit) is the E.M.F. which overcomes the resistance losses in the armature circuit. In our case the resistance of the armature circuit is zero, and consequently the dynamic E.M.F.

generated in the armature winding by its rotation in the excitation flux must equal, at all times, the static E.M.F. induced in this winding by the transformer flux.

We can now obtain the relation between these fluxes. Thus, if we consider a sinusoidal flux distribution and a distributed armature winding, we have the dynamic E.M.F.

$$(E_d) = \frac{4}{\sqrt{2}} \Phi_e T \frac{np}{120} \times 10^{-2}, \quad (17)$$

and the static E.M.F.

$$(E_s) = 4 \cdot \frac{\pi}{2\sqrt{2}} \cdot \frac{2}{\pi} \cdot T \Phi_i f \times 10^{-2}, \quad (18)$$

where Φ_e, Φ_i denote the maximum values (in megalines) of the excitation and transformer fluxes respectively, T denotes the turns in series between the brushes, and n, p, f denote respectively the speed in revolutions per minute, the number of poles, and the frequency of the supply.

Therefore, since $E_d = E_s$, we have

$$\frac{4}{\sqrt{2}} \Phi_e T \frac{np}{120} \times 10^{-2} = \frac{4\pi}{2\sqrt{2}} \cdot \frac{2}{\pi} \cdot T \Phi_i f \times 10^{-2},$$

whence
$$\Phi_e \times \frac{np}{120} = \Phi_i \times f.$$

If n_s is the synchronous speed of the motor in revolutions per minute, then $n_s = \frac{120f}{p}$, or $f = \frac{n_s p}{120}$; and, on substituting for f in the above equation, we obtain the relation

$$\begin{aligned} \Phi_e n &= \Phi_i n_s, \\ \text{or } \frac{\Phi_i}{\Phi_e} &= \frac{n}{n_s} \end{aligned} \quad (19)$$

Hence, at synchronous speed, we have $\Phi_i = \Phi_e$, and therefore the resultant flux is a revolving one of constant magnitude. At speeds below synchronism, Φ_i is smaller than Φ_e ; while, at speeds above synchronism, Φ_i is greater than Φ_e . Hence, under these conditions, the resultant field is elliptical. In commercial machines, due to losses and magnetic leakage, the resultant field is always of an elliptical nature, the minimum eccentricity occurring at a speed slightly above synchronism.

Now the ampere-turns producing the transformer flux must be the resultant of the armature ampere-turns and the ampere-turns produced by the stator winding T (Fig. 49). But the resultant ampere-turns along the energy axis of the motor differ 90 degrees in (time) phase from the ampere-turns produced by this winding. Therefore *the armature ampere-turns must have two components*, viz. one component in phase-opposition to the ampere-turns produced by the stator winding T , and the other component in (time) phase with the resultant ampere-turns. Thus, in the vector diagram of Fig. 51, the ampere-turns producing the transformer flux are represented by OD , and the ampere-turns due to the stator winding T are represented by OB . Hence the armature ampere-turns must be represented by OF , which is equal to the vector difference of OD and OB .

The vector OF , therefore, gives the phase of the armature current, the magnitude of which is represented by OI_a . The components of this current—which produce the components OC and OD of the armature ampere-turns—are represented respectively by OI_s and OI_d . The component OI_s may be considered as the compensating current to the current in the stator winding.

When the armature is stationary, the resultant ampere-turns along the energy axis must be zero; and, if the stator ampere-turns due to the winding T are represented by OB , the armature ampere-turns must be represented by $-OB$ or OC . Hence, for the same value of the stator current, *the armature current is greater when the armature is running than when the armature is stationary.*

It will now be convenient to complete the vector diagram for this motor. In Fig. 51 the transformer and excitation fluxes are represented, in magnitude and (time) phase, by OX and OY respectively.

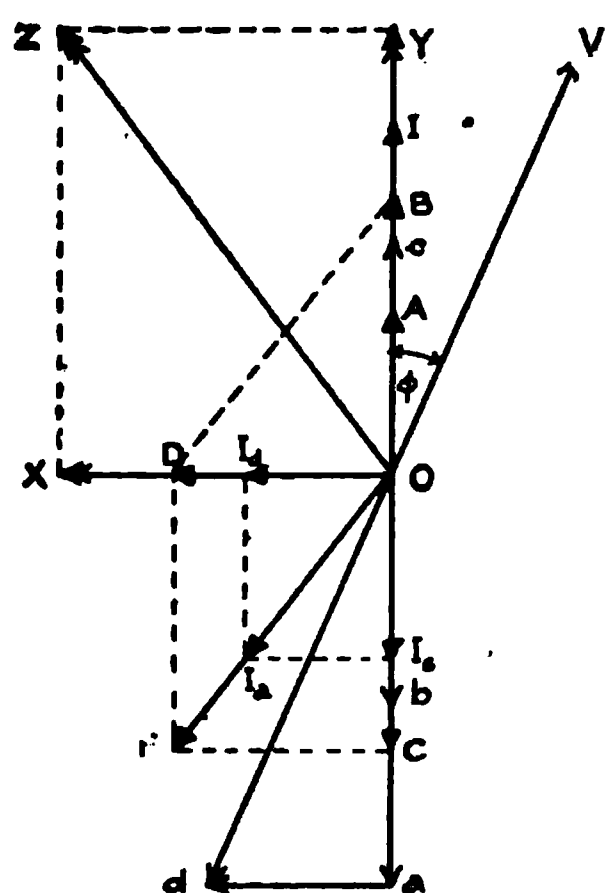


FIG. 51.

The resultant flux is, therefore, represented in magnitude and phase by OZ . The stator current is represented by OI , and the components of the stator ampere-turns, due to the windings E and T, are represented respectively by OA and OB . (These components are in time-phase, but are 90 degrees apart in space.) The dynamic E.M.F. (E_d) generated in the armature by its rotation in the excitation flux (OY) is represented by Oa , while the static E.M.F. (E_s) induced in the armature by the transformer flux (OX) is represented by Ob . The E.M.F. induced in the stator winding T by the transformer flux is represented by Oa ; the E.M.F. induced in the stator winding E by the excitation flux is represented by ad ; and the internal voltage of the motor (i.e. the vector sum of Oa and ad) is represented by Od . Thus the terminal voltage is given by OV and the power-factor by $\cos \phi$. The power supplied

to the motor is given by $OI \times OV \cos \phi (=OI \times Oa)$, and the output is given by $OI_s \times Oc$ or $OI_s \times Ob$. If k denotes the ratio between the armature turns and the turns in the stator winding T, then $OI_s = \frac{OI}{k}$, and $Ob = kOa$; so that $OI_s \times Ob = OI \times Oa = OI \times OV \cos \phi$.

Operating Features.—On account of the above relation between the transformer and excitation fluxes, it follows that as the speed increases, OX will increase and OY will decrease, so that the power-factor will improve.

That the machine has a series characteristic is evident from the manner in which the excitation flux is supplied to it. Moreover, in the motor with a single stator winding (Fig. 48) the speed for a given current depends on the position of the brushes.

In virtue of the uniformly rotating field at synchronous speed, the repulsion motor possesses operating features which are unique among alternating current machines. Thus, at synchronous speed, there is no

core loss in the armature, and there are no circulating currents in the coils undergoing commutation,* so that the commutation will only be influenced by the reactance voltage.

At speeds above synchronism, however, the transformer flux increases rapidly with the speed,† thereby resulting in large core losses and heavy circulating currents in the commutated coils. These conditions limit the operating speeds of repulsion motors to the neighbourhood of synchronous speeds, and where higher speeds are required it is necessary to provide means for weakening the transformer flux in the commutating zone.

On low-frequency systems the repulsion motor must, inherently, be a low-speed machine with relatively few poles. Thus, at 15 frequency, the synchronous speeds (which may be considered as the full load, or rated, speeds of the motor) are :

Number of poles	4	6	8	10
Synchronous speed (r.p.m.)	450	300	225	180

A repulsion motor for operating at this frequency will, therefore, be considerably heavier than a series motor, since the rated speed of the latter would be chosen to correspond to about twice synchronous speed, thereby resulting in a machine with more poles and a lighter magnetic circuit than a repulsion motor. It is apparent, then, that the low frequencies (15 cycles and below) which are desirable for series motors, do not lead to economical proportions in repulsion motors, and the latter machines are better suited for moderate frequencies of 25 cycles and upwards.‡ On the other hand, the operating voltage of a repulsion motor is not limited to low voltages, such as would be required for a series motor; in fact, the stator winding of a repulsion motor can be designed for the full line voltage in the same manner as that of a polyphase motor.

Having discussed the principal features of the ordinary repulsion motor (which features are to some extent common to all classes of repulsion motors), we will now consider the modifications of this motor which have been developed to suit the requirements of electric traction.

THE COMPENSATED-REPULSION MOTOR

The compensated-repulsion' motor is represented diagrammatically in Fig. 52, which should be compared with Fig. 49 (p. 67). The axis

* Since the resultant field is stationary relative to the armature, the transformer field Φ_t may be regarded as a commutating field for the coils short-circuited by the brushes. At synchronism, the dynamic (or commutating) E.M.F. generated in these coils by their motion in the flux Φ_t exactly neutralises the static (or transformer) E.M.F. induced by transformer action from the flux Φ_t . At speeds below synchronism, the commutating E.M.F. is smaller than the transformer E.M.F., while, at speeds above synchronism, the commutating E.M.F. becomes too strong, and in both these cases circulating currents will be produced in the coils undergoing commutation.

† If Φ_t is the value of the transformer field at synchronous speed (n_s), then, at a speed n , the transformer field will have a value given by

$${}_n\Phi_t = {}_s\Phi_t \left(\frac{n}{n_s} \right)^2$$

‡ In this connection see an article on "The Calculation of Single-phase Commutator Motors," by J. Fischer-Hinnen (*The Electrician*, vol. 63, p. 939).

of the short-circuited brushes coincides with the axis of the stator winding T, while at right angles to the former is another set of brushes (called the "*exciter brushes*"), which are connected either directly in series with the stator winding (Fig. 52a) or to the secondary of a current transformer,* the primary of which is in series with the stator winding, as indicated in Fig. 52b. From a comparison of Figs. 49 and 52a it will be apparent that the position of the exciter brushes (Fig. 52a), and their connection in series with the stator winding T, is equivalent to the *transfer of the excitation winding (E) of Fig. 49 to the armature*.

Hence, in the compensated-repulsion motor, the armature winding fulfils three functions, viz. : (1) it acts as a compensating winding to the stator winding T ; (2) it forms the excitation winding ; (3) it is the means whereby the transformer flux Φ_t is produced. As the number of turns in the excitation winding is now equal to the armature turns, it is only in special cases that the exciting current will be equal to the

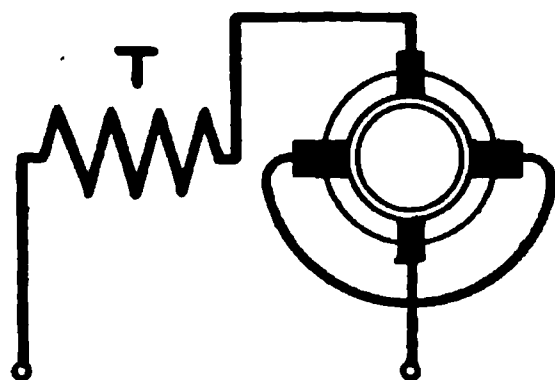


FIG. 52a.

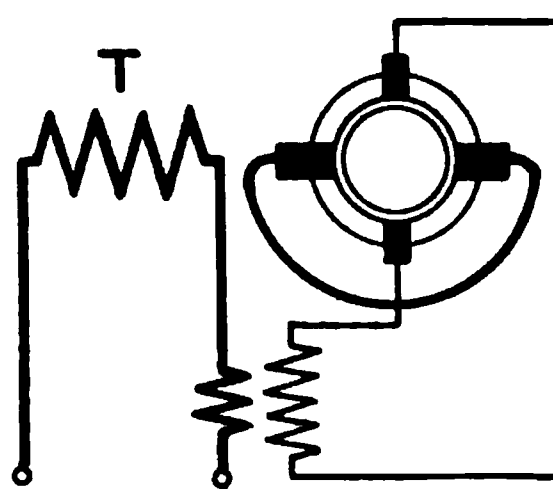


FIG. 52b.

main (stator) current. In other cases, the required value of the exciting current (to give the correct number of exciting ampere-turns) will have to be obtained from a current (or auto-) transformer in the main circuit.

The utilisation of the armature winding for excitation purposes introduces two important advantages into the performance of the motor : first, the leakage flux—which occurs between the armature and field windings in normal machines—is entirely eliminated ; and second, practically complete compensation of the inductive voltage in the excitation winding can be obtained at a certain speed, so that at this speed *the motor will operate at practically unity power-factor*.

The **phase-compensation** is obtained in the following manner. When the armature is rotating, the resultant (revolving) flux may be resolved into two components (viz. the excitation flux Φ_e and the transformer flux Φ_t), which are displaced 90 degrees from each other in time and space, as in the ordinary repulsion motor. The rotation of the armature in the transformer flux Φ_t produces a dynamic E.M.F. (called the compensating E.M.F.) between the exciter brushes, which is proportional to $(\Phi_t \times n)$, and is in phase-opposition with the flux Φ_t . Hence this dynamic E.M.F. has a phase-difference of 90 degrees (leading) from the excitation flux Φ_e and the exciting current (assuming the latter to be in phase with the excitation flux Φ_e).

Now the E.M.F. of self-induction, produced by the exciting current

* An auto-transformer can be used on low voltage machines.

in the armature winding, has a phase-difference of 90 degrees (lagging) from the exciting current. Therefore the dynamic E.M.F. will tend to neutralise, or compensate, the E.M.F. of self-induction. A reference to the space diagrams of Fig. 53 will confirm this result.

In the case of an ideal motor, we have shown that the transformer flux is equal to the excitation flux when the armature is running at synchronous speed; and since the compensating E.M.F. is proportional to $(\Phi_t \times \frac{np}{120})^*$ while the E.M.F. of self-induction is proportional to $(\Phi_s \times f)$, it follows that these two E.M.Fs. will exactly neutralise each other at synchronous speed, thereby giving a power-factor of unity.

Further consideration shows that, at speeds above synchronism (when Φ_t is greater than Φ_s), over-compensation of the inductive voltage will occur, and the stator current will lead the terminal voltage; while, at speeds below synchronism, under-compensation will take place.

FIG. 53.—Space Diagrams for Compensated-Repulsion Motor. NOTE.—The right-hand diagram has a time phase-difference of 90° (lag) from the left-hand diagram. The directions of the E.M.Fs. in the armature conductors are indicated in the diagrams.

In commercial machines, due to leakage reactance, hysteresis, and resistance, Φ_t will not be equal to Φ_s at synchronous speed, and these fluxes will not be exactly in quadrature; so that the maximum power-factor—which may be slightly less than unity—will occur at a speed slightly above synchronism.

Let us now consider the commutation at the two sets of brushes. Obviously, at synchronous speed, we have only to consider the reactance voltage in the commutated coils. At other speeds, the commutating conditions at the short-circuited brushes will be of exactly the same nature as those in the plain repulsion motor, and if operation at hyper-synchronous speeds is required, a local commutating flux (in opposition to the transformer flux) must be provided. On the other hand, the commutating conditions at the exciter brushes are perfectly satisfactory at all practicable speeds, and only the reactance voltage has to be considered. Thus, at starting, the transformer flux Φ_t is small, so that the E.M.F. induced by this flux in the coils short-circuited by the exciter brushes will be small; while, when the armature is rotating, the E.M.F. induced in these coils by the transformer action of the flux Φ_t is, in an ideal motor, exactly neutralised by the dynamic E.M.F. generated by the rotation of these coils in the exciting flux Φ_s .

* Refer to the equations, on p. 69, for the dynamic and static E.M.Fs. in the main circuit of the armature.

of which is known from E_s) are the resultant of the stator ampere-turns and the armature ampere-turns. Hence, if OC (along OX) represents the ampere-turns to produce the transformer flux, and OD represents the stator ampere-turns, then OE will represent the ampere-turns due to the resultant armature current. This current, as has already been shown (see p. 70) is due to two components in quadrature, one of these components being in phase-opposition with the stator current, while the other component is in phase with the transformer flux.

In the diagram for a commercial motor we have to consider the effects of resistance, magnetic leakage, leakage-reactance, hysteresis, and circulating currents (in the coils undergoing commutation at the short-circuited brushes). Moreover, we have two currents in the armature winding, viz. the exciting current and the main current. An examination of Fig. 55 will show that these currents do not interfere with each other, but simply result in an unequal distribution of current in the different portions of the armature winding. If r is the resistance of the armature between each set of brushes, I_a the current passing through the short-circuited brushes, and I the exciting current, the total resistance loss in the armature is equal to

$2(\frac{1}{2}I_a - \frac{1}{2}I)^2r + 2(\frac{1}{2}I_a + \frac{1}{2}I)^2r = I_a^2r + I^2r$,
and the voltage drop in the armature is equal to $I_ar + Ir$. Thus each current produces its own resistance drop in exactly the same manner as if the other current were non-existent.

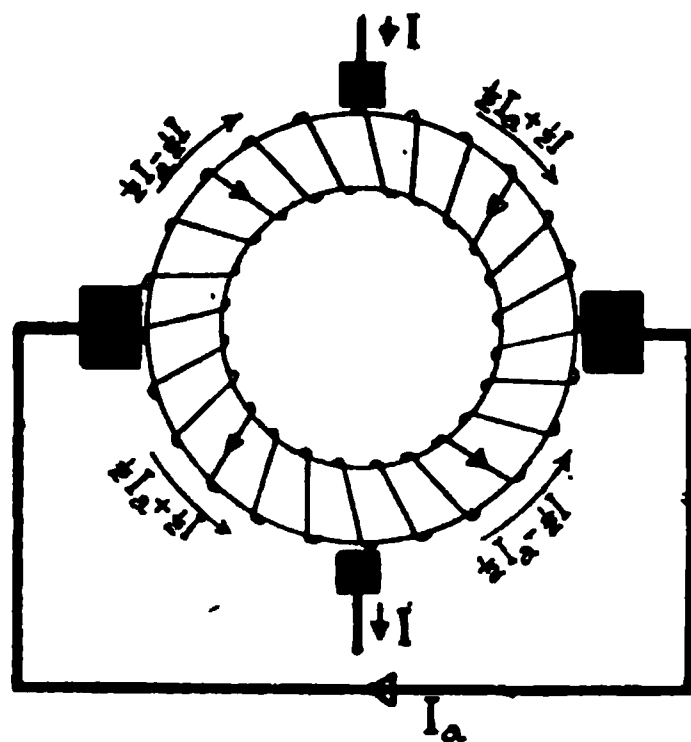


FIG. 55.

In constructing the general diagram of Fig. 56, the reaction of the circulating currents upon the excitation flux Φ_e is obtained in a manner similar to that adopted for the series motor (see p. 65), and is shown in Fig. 56a. In this diagram, OY represents the excitation flux, and OX the transformer flux. The transformer E.M.F. induced in the commutated coils by the excitation flux is represented by Oz , the dynamic (or commutating) voltage generated in these coils by their rotation in the transformer (or commutating flux) is represented by zy ,* while the reactance voltage is represented by yx ,* thereby giving a resultant voltage in the commutated coils which is represented by Ox . The circulating currents—and consequently the ampere-turns produced by them—may be considered to be in phase with Ox .

Hence, if OB (Fig. 56) represents the saturation ampere-turns required for the excitation flux Φ_e , the ampere-turns to be produced by the excitation winding will be represented by OA —the vector difference of OB and the ampere-turns (OC) due to the circulating currents. The phase of the exciting current—and also that of the stator current—can, therefore, be represented by OA .

Along OY set off Ob to represent the dynamic E.M.F. (E_d) gene-

* The phase and magnitude of zy and yx must be provisionally assumed, and afterwards checked when the phase and magnitude of the transformer flux and the main armature current are obtained.

rated in the armature by its rotation in the flux Φ_e (the magnitude of this voltage is known when the speed and Φ_e are known). The static E.M.F. (E_s) induced in the armature by the transformer flux must be sufficient not only to neutralise E_a , but also to overcome the impedance voltage due to the main armature current. Therefore, compound with Ob the impedance triangle bcd due to the main armature current, the phase and magnitude of which must be assumed. Then Od is equal to, and in phase-opposition with, the static E.M.F. (E_s) which must be induced in the armature by the transformer flux Φ_t , the magnitude and phase of the latter being represented by OX (at right angles to Od).

Along OX set off OD to represent the ampere-turns necessary to send

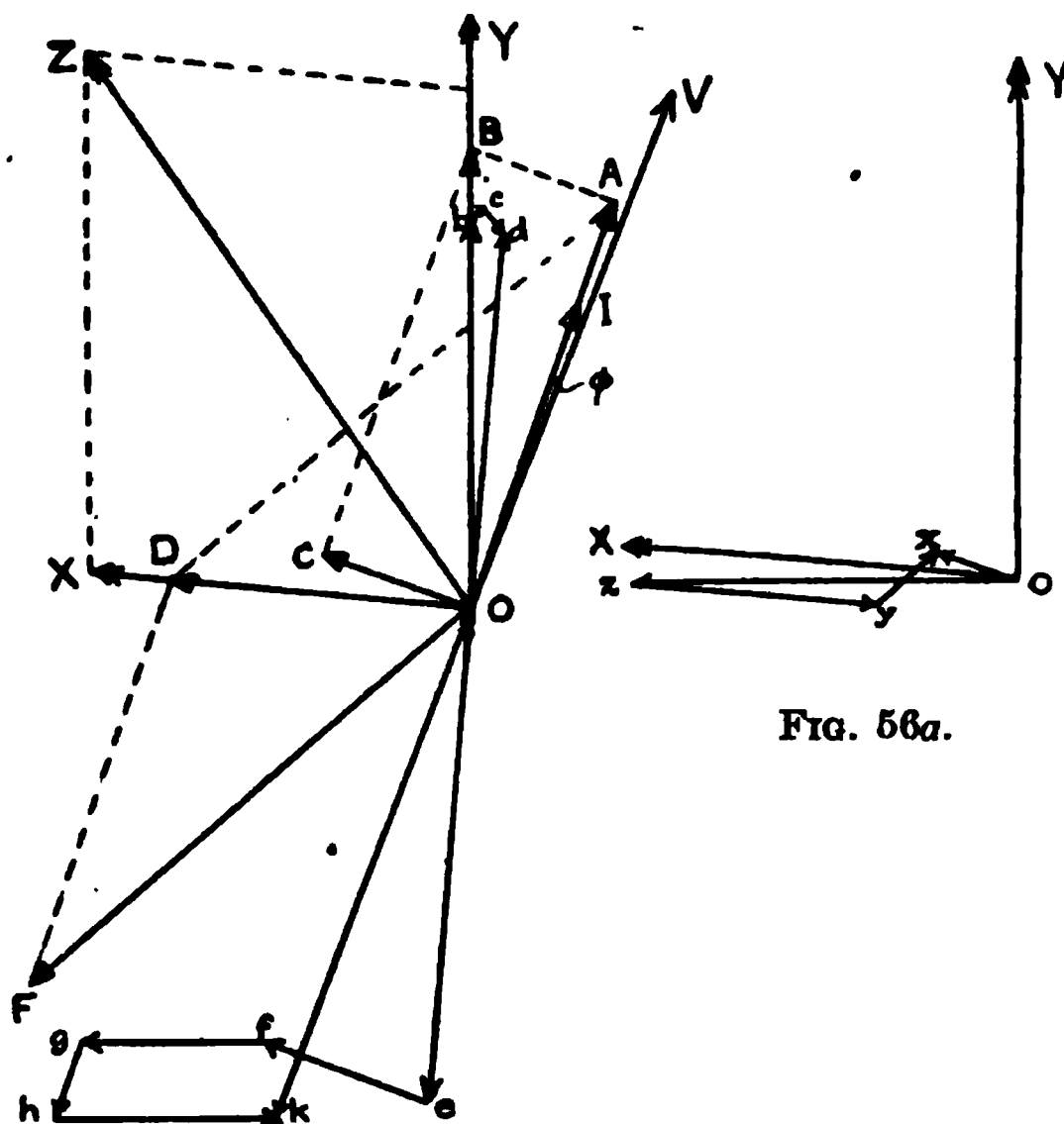


FIG. 56a.

FIG. 56.

this flux (Φ_t) through the magnetic circuit. These ampere-turns must be the resultant of the armature ampere-turns (due to the main current) and the stator ampere-turns. The latter are represented by OA , and therefore the armature ampere-turns are given by OF , which also represents the phase of the main armature current.

We will now obtain the terminal voltage of the motor. In the present case this voltage is the resultant of five different voltages, viz. :

(1) The E.M.F. induced in the stator winding by the transformer flux—represented by Oe (in phase-opposition to Od).

(2) The E.M.F. due to the leakage reactance of the stator winding and the current transformer (if any)—represented by ef (at right angles to OA).

(3) The E.M.F. of self-induction in the exciting circuit of the armature winding—represented by fg (at right angles to OY).

(4) The resistance drop in the exciting circuit of the armature winding—represented by gh (parallel to OA).

(5) The compensating E.M.F. in the exciting circuit, due to the rotation of the armature in the transformer flux OX —represented by hk (parallel to OX).

Hence the internal voltage of the motor is represented by Ok , while OV —equal and opposite to Ok —represents the terminal voltage.

THE SERIES-REPULSION (OR DOUBLY-FED) MOTOR

This motor is a modification of the repulsion motor, and is capable of operating satisfactorily at speeds considerably above synchronism. Thus the principal objection to the repulsion motor (viz. the restriction to speeds in the neighbourhood of synchronism) is overcome. It is probable that for low-frequency circuits the doubly-fed motor will compete

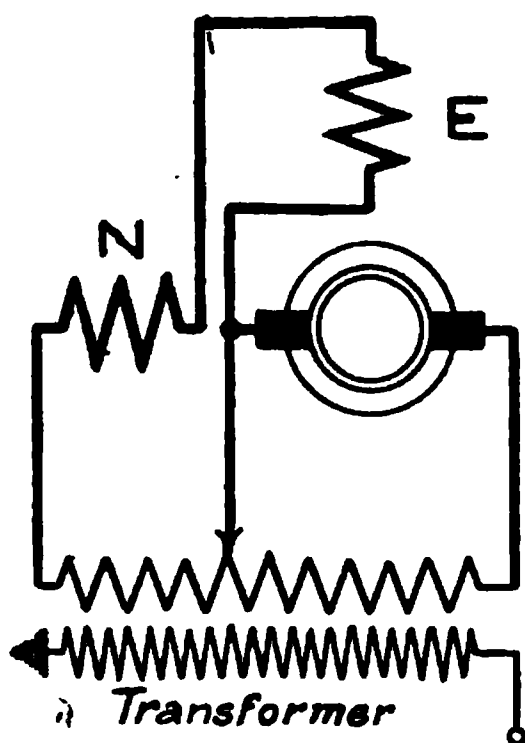


FIG. 57a.

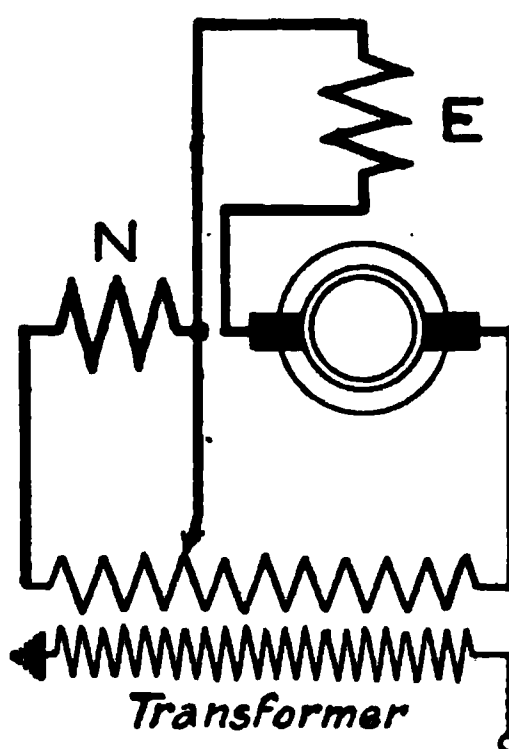


FIG. 57b.

successfully with the series motor, while it will entirely supersede the compensated-repulsion and simple-repulsion motors.

The characteristic feature which distinguishes this motor from all other series and repulsion motors is that the motor possesses a transformer- or cross-field *which can be regulated*, so that satisfactory commutation can be obtained over a very wide range of speeds.

As far as constructional features are concerned, the doubly-fed motor resembles a repulsion motor for reversible operation (see Fig. 49), and the stator has two distributed windings with their magnetic axes at right angles to each other. The armature, however, is arranged for connection to the supply circuit, either independently of the stator windings (as in Fig. 57a) or in conjunction with one of the stator windings (as in Fig. 57b). Hence the currents in the armature and stator windings differ from each other.

At starting, the brushes may be short-circuited, so that the machine operates as a repulsion motor, and the connections may be changed automatically at synchronous speed, so that the machine operates as a doubly-fed motor. In many cases, however, satisfactory operation may be obtained by operating the machine throughout as a doubly-fed motor.

When connected as a doubly-fed motor, energy is transmitted from the stator to the armature in two ways, viz. (1) directly, through the connection of the brushes to the stator circuit, and (2) indirectly, by means of the transformer flux, as in the repulsion motor. The higher the speed is above synchronism, the greater is the percentage of the energy transmitted directly to the armature, so that, under these conditions, the operating features of the machine resemble those possessed by a series motor. At speeds in the neighbourhood of synchronism, the armature receives practically the whole of its energy indirectly, and the operating features of the machine are then similar to those possessed by a repulsion motor.

Let us now obtain, for an ideal motor, the relations between the speed, the fluxes, and the voltage to be applied to the armature, in order to obtain satisfactory operation at hyper-synchronous speeds. If we neglect the reactance voltage in the commutated coils, then the condition for ideal commutation is that the transformer-E.M.F. induced in the commutated coils by the excitation flux shall be neutralised by the dynamic-E.M.F. generated in these coils by their rotation in the transformer flux. Hence, if ${}_n\Phi_e$, ${}_n\Phi_t$ denote respectively the excitation and the transformer fluxes at an armature speed n , and Φ'_t denotes the value of the transformer flux required for ideal commutation, then $\Phi'_t = {}_n\Phi_e \frac{n_s}{n}$

(n_s being the synchronous speed). But $\frac{{}_n\Phi_e}{{}_n\Phi_t} = \frac{n_s}{n}$ (see p. 69), whence

$\Phi'_t = \left(\frac{n_s}{n}\right)^2 {}_n\Phi_t$. Therefore, in order to obtain ideal commutation at this speed (n), the transformer flux ${}_n\Phi_t$ must be reduced to $\left(\frac{n_s}{n}\right)^2 {}_n\Phi_t$,

while the excitation flux must retain its value ${}_n\Phi_e$. If, however, the transformer flux is reduced, the speed of the motor will be affected, since the dynamic-E.M.F.—generated in the armature by its rotation in the excitation flux—must, at all times, balance the static-E.M.F. induced in the armature by the transformer flux. It is apparent, then, that if the speed is to be maintained at its original value (n), an E.M.F. must be introduced into the armature—*via* the brushes—in order to equalise the dynamic- and static-E.M.Fs.

If E_d , E_s , E'_s denote respectively the E.M.Fs. in the armature due to the fluxes ${}_n\Phi_e$, ${}_n\Phi_t$, ${}_n\Phi'_t$, and E_x denotes the external E.M.F., corresponding to a speed n , then $E_d = K \cdot {}_n\Phi_e \cdot n$; $E_s = K \cdot {}_n\Phi_t \cdot n_s$; $E'_s = K \cdot {}_n\Phi'_t \cdot n_s = K \left(\frac{n_s}{n}\right)^2 {}_n\Phi_t n_s$ (see p. 69).

Since $E_x + E'_s = E_d$, and $E_s = E_d$, we have $E_x = E_s - E'_s$, or

$$E_x = E_s \left(1 - \frac{E'_s}{E_s}\right) = E_s \left(1 - \left(\frac{n_s}{n}\right)^2\right). \quad \dots \dots \dots (20)$$

Now, when the machine is running as a repulsion motor, the E.M.F. (E) induced in the transformer axis of the stator winding—by the transformer flux ${}_n\Phi_t$ —may be represented by kE'_s , (k being the ratio of transformation), and this E.M.F. is equal in magnitude to the energy component of the stator terminal voltage. Therefore, in the doubly-fed

motor, the energy component of the supply voltage must be divided between the stator and the armature in the ratio of $k \left(\frac{n_s}{n}\right)^2 : \left(1 - \left(\frac{n_s}{n}\right)^2\right)$.

At speeds considerably in excess of synchronism, practically the whole of the energy input to the motor is supplied directly to the armature.

At speeds below synchronism the transformer flux must be increased, and a reversed voltage must be applied to the armature. It is, however, more difficult to obtain ideal commutation under these conditions, as the saturation of the magnetic circuit imposes a limit to the magnitude of the transformer flux. Hence, if the machine is to be operated throughout as a doubly-fed motor, the circulating currents, at low speeds, must be kept within reasonable values by methods similar to those adopted in series motors. These objections are removed by starting the machine as a repulsion motor and changing it to a doubly-fed motor during the accelerating period.

The doubly-fed motor, therefore, combines the advantages of a repulsion motor with those of a series motor, and enables satisfactory operation to be obtained over a wide range of speeds. The voltage of the motor cannot be selected in the same arbitrary manner as that of a repulsion motor, but it is permissible to adopt voltages higher than those required by series motors.

THE BRUSH-SHIFTING REPULSION (OR DÉRI) MOTOR

In the above discussion of the simple repulsion motor we stated that the torque and speed were influenced by the position of the brushes. Hence it would be possible theoretically to control the speed of the motor by shifting the brushes. In practice, however, such a method of control has several disadvantages; thus, the machine would be very sensitive to brush position (i.e. a small movement of the brushes would produce a large variation in the torque), while, when the brushes were in the position corresponding to zero torque, excessive circulating currents would be produced in the armature coils short-circuited by the brushes.

These objections are overcome, in the Déri repulsion motor, by the use of a double set of brushes, one set being fixed permanently in position — with the axis of the brushes coinciding with the axis of the stator winding — while the other set is arranged on a movable rocker, so that these brushes

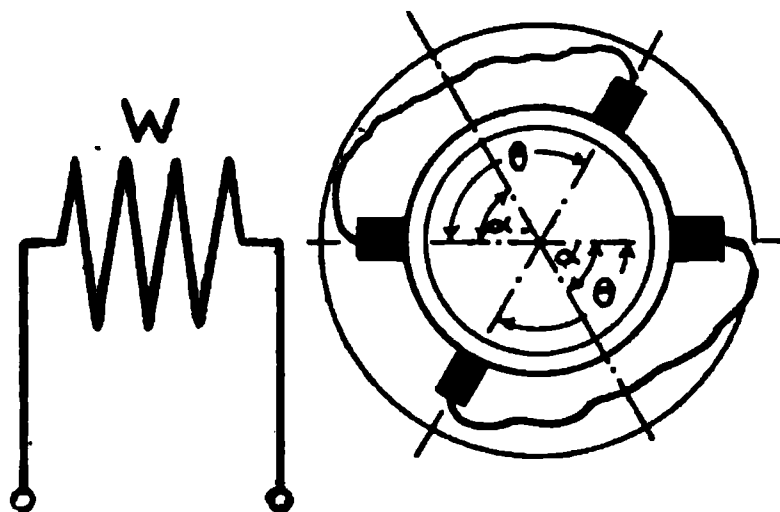


FIG. 58.

can be displaced relatively to the fixed brushes. The fixed and movable brushes are interconnected in the manner indicated in Fig. 58, which represents diagrammatically the connections of a two-pole motor. If this diagram be compared with that for the simple repulsion motor (see Fig. 48, p. 66), it will be found that, in one case (Fig. 48), the magnetic axis of the armature coincides with the axis of the brushes; while, in the other case (Fig. 58), the magnetic axis of the

armature coincides with the line bisecting the angle between the fixed and movable brushes which are interconnected. In each diagram (Figs. 48, 58) the angle between the magnetic axes of the stator and armature is denoted by α , which, for the simple repulsion motor, corresponds to the angle of displacement of the brushes from the position of zero torque; but with the Déri motor this angle (α) corresponds to only one-half of the angle of displacement of the brushes (θ). Hence, in the Déri motor, the brush displacement corresponding to the two positions of zero torque is 180 degrees, as against 90 degrees in the case of the ordinary repulsion motor.

But there are other differences of considerable importance. Thus, when the movable brushes are in line with the fixed brushes to which they are connected ($\theta=0^\circ$), there is no current in any portion of the armature winding. Consequently, when the stator is excited, only the magnetising current will pass into the stator winding. Moreover, when the movable brushes are displaced from the fixed brushes, only a portion of the armature conductors, viz. those embraced in the angle of brush displacement (see Fig. 58), are acted upon by the stator winding. Hence the torque will increase gradually with the brush displacement, and, in general, the maximum torque will correspond to a large brush displacement.*

The Déri motor possesses the same general operating characteristics as the simple repulsion motor. It is, however, essentially an adjustable speed machine, as well as a variable speed one, and therefore the speed control of the motor in either direction of rotation is much simpler than with other types of repulsion motors. Moreover, by means of resistance connected between the brush sets it is possible to alter the character of the speed curve and to obtain regenerative braking.†

The **commutation** at speeds in the neighbourhood of synchronism is equal to that of other types of repulsion motors, and is unaffected by the position of the brushes. At other speeds the commutating conditions at the two sets of brushes are not identical, and while it is possible to improve the commutation at the fixed brushes by means of auxiliary devices (e.g. commutating poles), these devices cannot be used in connection with the movable brushes on account of their variable position.

It will be of interest to discuss the **manner in which the operation and commutation are influenced by the double set of brushes and the brush displacement**. As the number of active armature conductors and also the magnetic axis of the armature are not constant, but depend on the brush displacement, it will be necessary to resolve the active armature turns—corresponding to a given brush displacement θ (Fig. 58)—into two components mutually at right angles, the direction of one component coinciding with the magnetic axis of the stator. Thus, in a two-pole machine, if θ is the angle of brush displacement, $\alpha (= \frac{1}{2}\theta)$ the angle between the magnetic axes of stator and armature, $2T$ the total number of armature turns, and I_a the total armature current, then the armature ampere-turns (which are equal to $I_a T \alpha / \pi$)

* By suitable design, it is possible to arrange for the maximum torque (with the armature stationary) to correspond to a brush displacement as large as 155 degrees, while the curve connecting torque and brush displacement may be made to approximate to a straight line for brush displacements above 90 degrees. See "The Control of Repulsion Motors by Brush Displacement," by K. Schnetzler (*The Electrician*, vol. 60, p. 438).

† See *Electric Motors*, Hobart, p. 678.

can be resolved into the components $I_a T a / \pi \cos \alpha$, in the direction of the stator axis, and $I_a T a / \pi \sin \alpha$ at right angles thereto. These components are represented in Fig. 59b by OP and OQ respectively, the total armature ampere-turns being represented by OR . Obviously we can consider that the components OP , OQ are produced by the armature current (I_a) circulating in two coils T, E (Fig. 59a)—at right angles to each other—if the number of turns in coil T are $T a / \pi \cos \alpha$, and those in coil E are $T a / \pi \sin \alpha$.

Since, with the armature stationary, the current I_a is produced by induction, the ampere-turns of the coil T must act in opposition to the stator ampere-turns. Hence the resultant ampere-turns in the direction PO will be $(IT_s - I_a T a / \pi \cos \alpha)$, where I is the stator current and T_s is the number of turns in the stator winding. If Φ_s is the flux produced (in

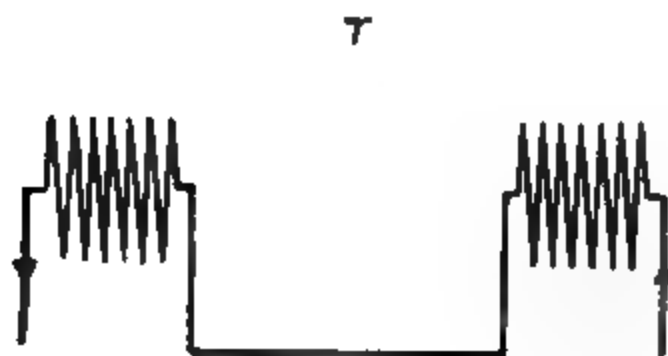


FIG. 59a.

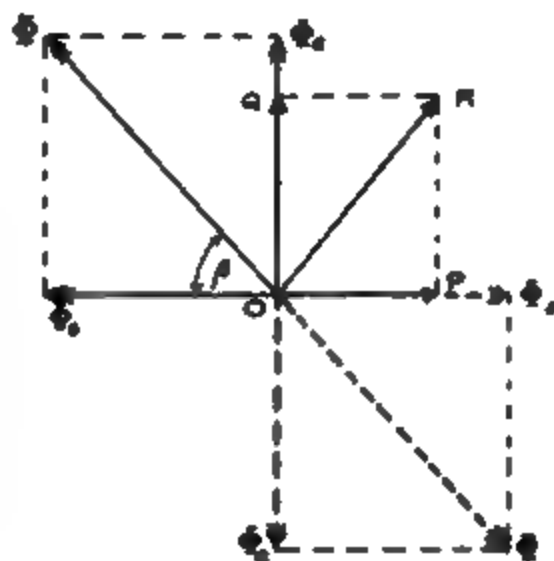


FIG. 59b.

the direction PO) by these ampere-turns, and Φ_s the flux produced by the component OQ of the armature ampere-turns, the resultant flux Φ will be given by $\Phi = \sqrt{\Phi_s^2 + \Phi_e^2}$, which will be displaced by an angle β ($= \tan^{-1} \frac{\Phi_e}{\Phi_s}$)

from the magnetic axis of the stator. The stator current (I) must be such that (neglecting losses and leakage) the flux Φ_s will induce in the coil T (Fig. 59a) an E.M.F. sufficient to overcome the E.M.F. induced in the coil E by the flux Φ_e . We have then conditions similar to those in the simple repulsion motor.

The magnitude and phase of the resultant flux Φ will vary with the position of the movable brushes. Thus, when the brush displacement (θ) is zero, $\Phi = \Phi_s$, $\beta = 0$, and $\Phi_e = 0$. The stator current will then be a minimum. When the brush displacement is 180 degrees, Φ_s , Φ_e , and Φ are all zero, and the machine is equivalent to a short-circuited transformer.

The torque is proportional to the product of the armature ampere-turns and the flux Φ : it is obviously zero when $\theta = 0$, and when $\theta = 180$ degrees. As the armature ampere-turns increase rapidly for brush displacements above 90 degrees, it follows that the maximum torque will occur at some brush displacement between 90 degrees and 180 degrees. It must be observed, however, that the coils short-circuited by the fixed brushes are subjected to transformer action from the flux Φ_s , and the

FIG. 60.—Stator and Frame of Westinghouse Single-phase Series Motor,
showing windings in position.

FIG. 61.—Stator and Frame of Westinghouse Single-phase Series Motor,
showing compensating winding in position.

FIG. 62.—Westinghouse Single-phase Series Motor with Armature Removed.

FIG. 63.—Detailed View of the Pole Faces and Brush-gear of a Westinghouse Split-frame Single-phase Series Motor.

circulating currents in these coils may prevent the utilisation of the maximum torque. In some cases the circulating currents are limited

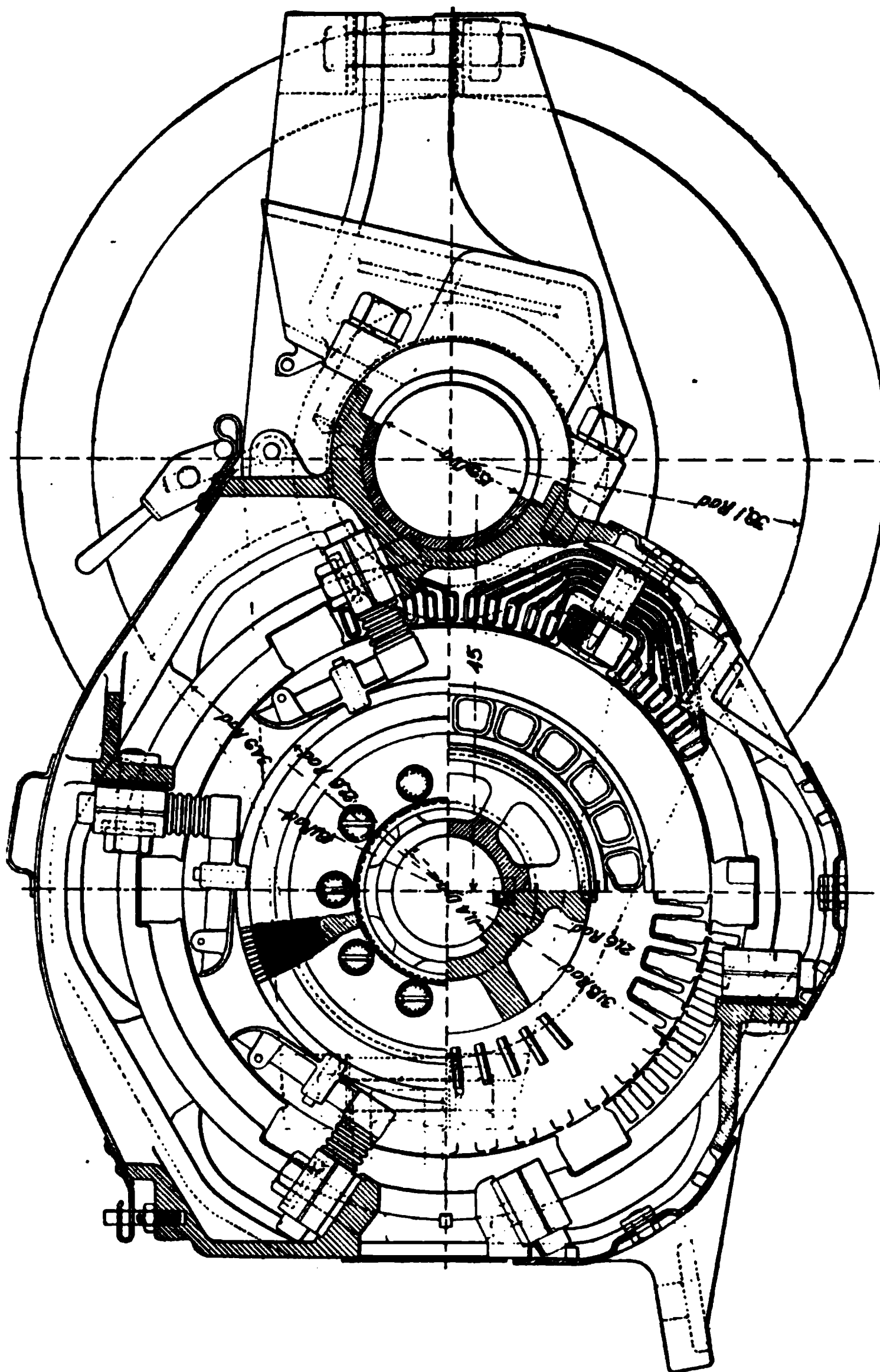


FIG. 64.—Cross-section of Westinghouse 180-H.P., 6-Pole, 25-Cycle, Single-phase Series Motor.
(Dimensions in centimetres.)

by increasing the reluctance in the path of the flux Φ_e (e.g. by arranging slots in the core so that they offer a high reluctance to the flux Φ_e , and a relatively low reluctance to the flux Φ_s).*

* See *The Electrician*, vol. 60, p. 439.

If we consider the armature to be revolving, then dynamic-E.M.Fs. will be generated in the coils T and E (Fig. 59a) due to their rotation in the fluxes Φ_s , Φ_a , and the resulting current will produce two fluxes Φ'_s , Φ'_a , at right angles to each other. These fluxes are in time-quadrature with the fluxes Φ_s , Φ_a , hence the resultant flux Φ_r will be given by $\Phi_r = \sqrt{(\Phi'_s)^2 + (\Phi'_a)^2}$; and it can be shown that this flux is at right angles, in space, to the flux Φ . Hence we have a revolving field produced in the same manner as in the simple repulsion motor. Moreover, it can be shown that this revolving field is uniform, at synchronous speed, for any angle of brush displacement (except $\theta=0$ and $\theta=180$ degrees), while at other speeds the revolving field is elliptical. Therefore, as far as the principle of the motor is concerned, we have characteristics exactly similar to those of the simple repulsion motor.

FIG. 65.—Armature of 150 H.P. Westinghouse Single-phase Series Motor.

Let us now consider commutation.

At synchronous speed, due to the uniformly revolving field, the commutating conditions do not require investigation.

At other speeds the coils short-circuited by the fixed brushes will have a static-E.M.F. induced in them by the flux Φ_s , while a dynamic- or compensating-E.M.F. will be produced in them by their rotation in the flux Φ'_s . Hence, since these fluxes are equal at synchronous speed, while with increasing speed Φ_s diminishes and Φ'_s increases, it follows that over-compensation will occur at hyper-synchronous speeds. The commutation, however, may be improved at these speeds by means of commutating poles, in a similar manner to other repulsion motors. As the flux Φ_s depends on the angle of brush displacement, the circulating currents at starting and at low speeds will only become objectionable for large brush displacements, i.e. corresponding to heavy loads and high torque.

The commutation at the movable brushes will depend on their position on the commutator. Thus in some positions the coils short-circuited by these brushes are subjected to maximum transformer action from the flux Φ'_s (which is, to some extent, compensated by the rotation of the coils in the flux Φ_s), while in other positions the coils are liable to have a relatively large dynamic-E.M.F. generated in them by their

rotation in this flux (Φ'_a), the opposing static-E.M.F. due to the flux Φ_a being relatively small. In general, more difficulty will be experienced from transformer action from the flux Φ'_a . This is particularly the case when the machine is operating at high speeds with a large brush dis-

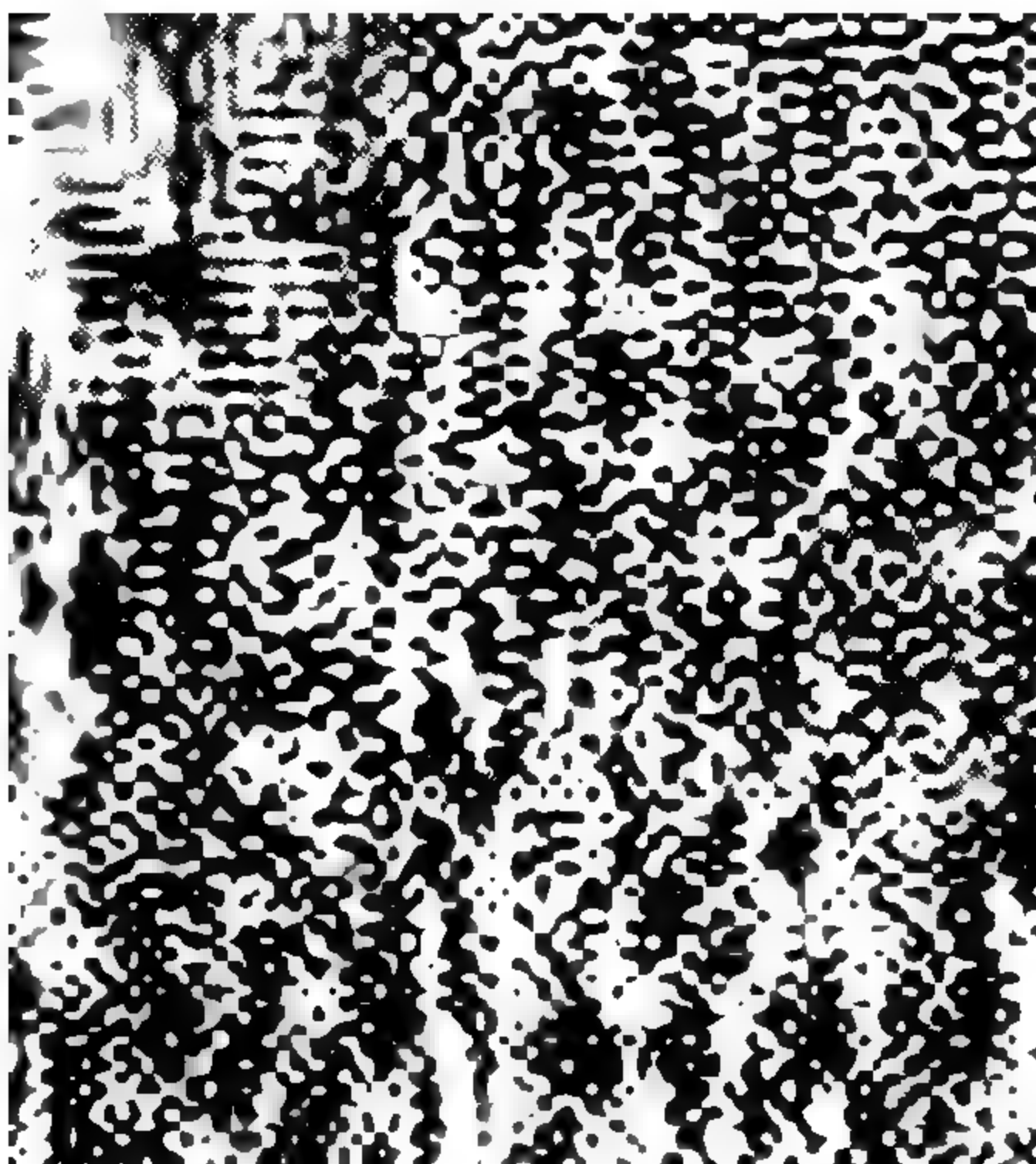


FIG. 66.—Completely-wound Stator of Oerlikon 1250 H.P. Single-phase Series Motor.

placement, as the compensating static-E.M.F., which is due to Φ_a , is relatively small.

GENERAL REMARKS ON SINGLE-PHASE MOTORS

All types of single-phase motors must be designed with a low flux per pole, low flux-densities, and small air-gaps. The low flux per pole is required for the purpose of limiting the transformer-E.M.F. at starting, while the low flux-densities and the small air-gaps are necessary

in order to reduce the exciting ampere-turns and improve the power-factor. Since the torque is proportional to the produce of flux and armature ampere-turns, it follows that, in single-phase motors, the armature ampere-turns must be relatively large in order to obtain the requisite torque. For instance, in series motors, the armature ampere-turns may be from 2 to 4 times greater than the field ampere-turns.

Now the maximum number of ampere-turns which can be carried by a given armature is limited by heating considerations (assuming that

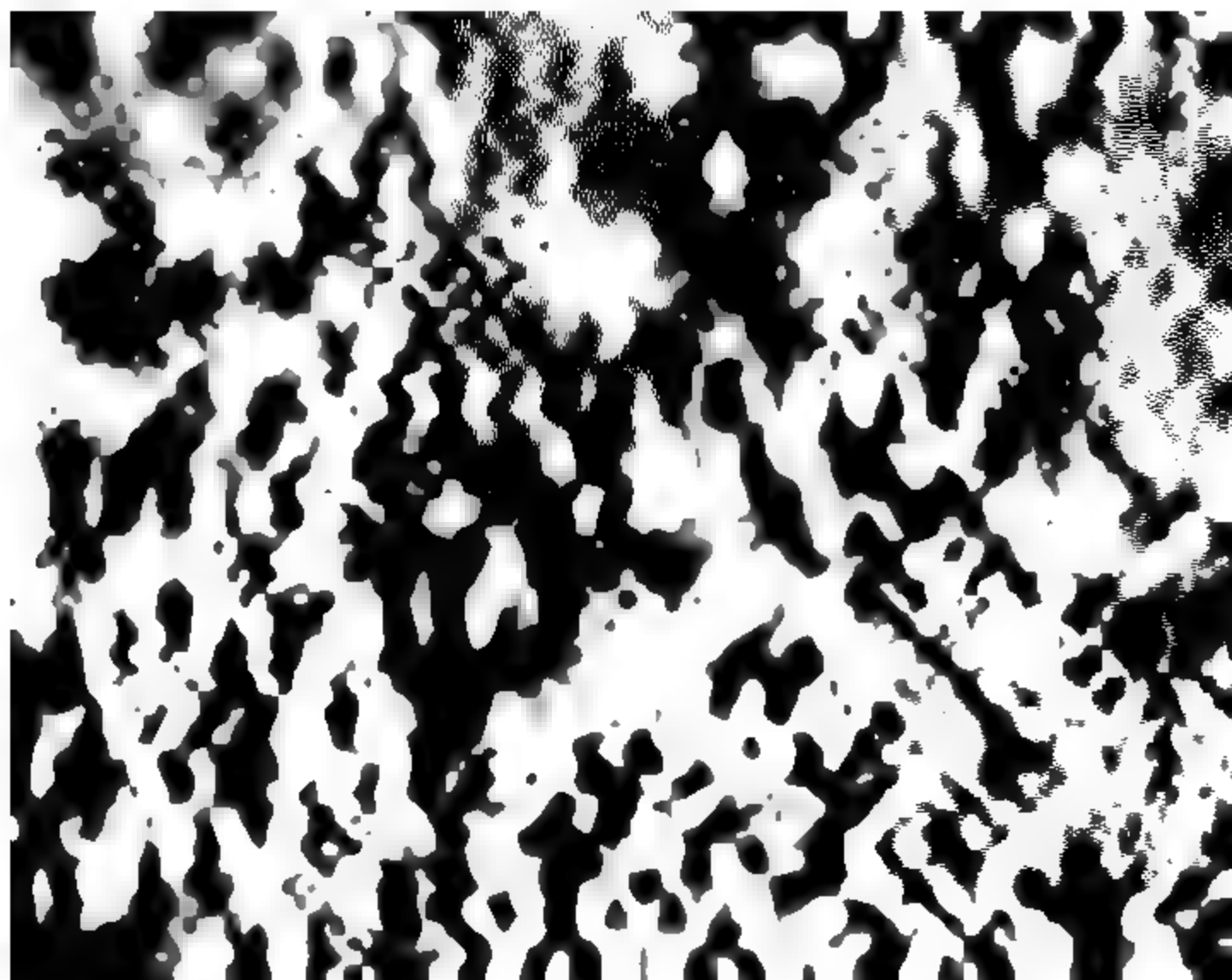


FIG. 67.—Armature of Oerlikon 1250 H.P. Single-phase Series Motor.

the armature reaction is neutralised), so that it will be desirable to adopt means for obtaining the maximum amount of ventilation. Thus the forced ventilation of single-phase motors forms an important feature in their design.

In the compensated-repulsion motor the armature has to carry the exciting ampere-turns in addition to the torque-producing ampere-turns. Hence it is apparent that the armature of a compensated-repulsion motor will, in general, be larger in diameter than that of a series motor. Moreover, it is also apparent that the armature of a series motor must be larger in diameter than that of a continuous-current motor of equal output and speed.

When the stator is considered, however, the low flux per pole, and the low number of ampere-turns to be supplied by the exciting winding,

will enable the stator core to be designed with a small radial depth of iron. In this feature the series motor, on account of its greater number of poles, possesses an advantage over the repulsion motor, especially for low-frequency circuits. The small radial depth of iron in the stator core is shown very clearly in the cross-sectional drawings of Figs. 64, 71 (pp. 84, 93).

The air-gap of series and repulsion motors is limited by considera-



Amperes Input

FIG. 68.—Characteristic Curves of Oerlikon 1250-H.P., 16-Pole, 15-Cycle, Single-phase Series Motor (1350 mm.—53.2 in.—wheels, 2.23:1 gear ratio). η =Efficiency; v =speed in km. per hour; L =H.P. output; Z =tractive-effort in kg. NOTE.—Efficiency curve includes losses in transformer and gearing.

tions of power-factor. In practice the air-gap is usually of the order of from 2 to 4 millimetres (0.08 in. to 0.16 in.),* the latter value only being permissible in motors of large output. With the compensated-repulsion motor it would appear that larger air-gaps are permissible, but limitations occur due to the fact that the exciting ampere-turns must be carried on the armature, and therefore, as these ampere-turns

* Appropriate values for the air-gap of continuous-current railway motors are 0.18 in. to 0.25 in.

do not increase the output, the adoption of large air-gaps would result in increased armature diameters.

The **operating voltage** of a series motor is closely connected with considerations of commutation, the limiting condition being the maximum permissible value of the E.M.F.s. which cause sparking. Of these E.M.F.s., the principal component is the transformer-E.M.F. Now, we have shown that the permissible values which can be adopted for the transformer-E.M.F. are dependent upon the subdivision of the armature winding and commutator. Consequently the number of commutator segments will, in general, govern the operating voltage of the motor,

% $\cos \phi$ v L

100 55 550

90 50 500

80 45 450

70 40 400

60 35 350

50 30 300

40 25 250

30 20 200

20 15 150

10 10 100

0 5 50

0 0 0

Amperes Input

FIG. 68a.—Characteristic Curves of Oerlikon 300-H.P., 10-Pole, 16½-Cycle, Single-phase Series Motor (1070 mm.—42.1 in.—wheels, 4.47 : 1 gear ratio). η = Efficiency; v = speed in km. per hour; L = H.P. output; Z = tractive-effort in kg. **NOTE.**—Efficiency curve includes losses in transformer and gearing.

and moderate voltages—of from 400 to 500 volts—will only be practicable with large motors.

With machines of moderate output the operating voltage must be chosen between 250 to 320 volts, and, in consequence, a large contact surface for the brushes will be required. Moreover, as the brushes must be of high contact resistance, the losses at the commutator will form a fairly large percentage of the total armature losses.

With repulsion motors, the transformer-E.M.F. at starting forms the limiting feature in the selection of the number of armature conductors, and consequently the armature winding and commutator of these motors must be subdivided in the same manner as those of series motors. Since, however, the armature voltage does not limit the terminal voltage, the former can be selected to such a value that resistance connections are unnecessary. In general the armature voltage will be

lower than that of a series motor of equal rating, so that the total contact surface of the brushes will be greater in the repulsion motor than in the series motor; while, with compensated-repulsion motors, additional brushes will be required for the exciting circuit.

It is apparent, therefore, that the losses in the armature and commutator of a single-phase motor will be considerable, and forced ventilation will be necessary in order to dissipate the heat produced by these losses.

With the relatively large losses in the armature, and the losses in the stator, it follows that the efficiency of the motor will be lower than that of a machine of equal output in which the losses are smaller, *e.g.* a continuous-current motor. Thus, in general, the **efficiency of single-phase motors** will be several per cent. lower than that of continuous-current motors of equal rating. In some cases, however, the increase in weight is not so great as might be anticipated. Obviously, to obtain a correct comparison between the weights of continuous-current and single-phase motors, we must have similar conditions in each case. For example, not only should the output and speed be equal in the two cases, but the efficiency, temperature rise, and ventilation should also be identical. The following **comparative weights** refer to actual motors of the ventilated type, but the speeds and efficiencies are not identical. The figures, however, will enable a general comparison to be formed between commercial motors.

Type of Motor.	1-hour Rating.			Efficiency at Rated Load. Per Cent.	Power- factor at Rated Load. Per Cent.	Weight of Motor without Gears. Lb.
	H.P.	Volts.	r.p.m.			
Continuous current .	160	600	500	87.5	...	4300
Single-phase neutralised series .	150	235	625	81	86	5500
Single-phase compen- sated repulsion .	150	750	775	82	98	5500

Operation of single-phase motors on continuous-current circuits.
—As the alternating-current series motor is identical in principle with the continuous-current series motor, it follows that the former type of motor is capable of operating on continuous-current circuits. The neutralising (or compensating) winding, however, must be excited conductively from the main circuit, as this winding is essential to satisfactory operation with continuous-current (on account of the high armature ampere-turns). Moreover, with motors of the non-salient-pole type, it will be necessary to provide a commutating field for continuous-current operation.

Examples of the operation of alternating-current series motors on alternating-current and continuous-current circuits are referred to in Chapter X. The motors are of the Westinghouse type (see p. 83) with salient poles, and are installed on certain locomotives of the New

Haven Railroad. These locomotives have to operate over the single-phase lines of the New Haven road, and also over the continuous-current lines of the New York Central Railroad. The dual operation, however, leads to considerable complication in the control, as well as to increased weight (see Chapter X, p. 239).

EXAMPLES OF SINGLE-PHASE RAILWAY MOTORS

(1) **Series motors.**—The simplest type of single-phase railway motor in operation is that developed by the **Westinghouse Companies**. This motor is of the neutralised-series type without commutating poles.



FIG. 60.—Method of connecting Auxiliary Armature Winding in Siemens' Single-phase Series Motors.

In Figs. 60 and 61 are given views of a 4-pole, 150 H.P. motor, showing the frame and stator with the winding in position. The stator laminations are assembled in a cast-steel frame, which carries seatings for the frame-heads and the axle-bearings. Since the frame is not required for magnetic purposes, a skeleton construction has been adopted, and large apertures are arranged in the frame at the back of the stator core for the purpose of cooling the latter.

The skeleton construction of the frame is shown better in the illustration in Fig. 62, which refers to a 12-pole motor, of 315 H.P., built by the Westinghouse Co., for the geared passenger and freight locomotives on the New Haven Railroad (see Chapter XVII, p. 383). The motor is mounted on the framing of the locomotive vertically above the axle (see Fig. 318, p. 384). The method of mounting the brush-gear should be noted.

A detailed view of the brush-gear and windings of a 250-H.P., 8-pole, split-frame Westinghouse motor* is given in Fig. 63. The armature of this motor is mounted concentric with the axle of the driving wheels, hence the necessity for a split frame.

In Fig. 64 is given a cross-section of a 180-H.P., 6-pole, Westinghouse motor, showing the general design of the armature and stator. An examination of the armature slots will show that they are of the partially closed type and are of two widths. The wider portion of the slot contains the armature conductors proper, while the narrower portion of slot contains the resistance connections, which connect the armature conductors to the commutator segments. In winding the armature, these resistance connections are first placed in the slots and connected to the commutator segments. The armature coils are then placed in the slots with the open ends of the coils away from the commutator, i.e. just in the reverse manner to that adopted in winding a continuous-

current armature. The open ends of the coils are then connected together in the correct order, and are finally connected to the resistance connections. A view of a completed armature is shown in Fig. 65.

The object of placing the resistance connections at the bottom of the slots is that the slot may be made narrower at the lower portion, and consequently a larger cross-section is obtained at the root of the tooth than with a slot of uniform width.

All the above motors are forced ventilated, the air being supplied from an external blower and conveyed to the motor through suitable ducts.

With the type of motor illustrated in Figs. 60, 64 the air is admitted through an opening in the pinion-end frame-head, and is discharged through the apertures in the frame. With the type of motor illustrated in Fig. 62 the air is admitted to the pinion end of the frame, and is circulated through the interior of the motor by means of a fan on the armature and suitable baffle plates, the air being expelled through the apertures in the frame. In this motor the armature core and commutator are provided with longitudinal ventilating ducts only.

The standard single-phase motors of the **Oerlikon Co.** have series-wound commutating poles in addition to neutralising and exciting windings. The commutating poles are excited in the manner described on page 61.

A completely wound stator for a 1250-H.P., 16-pole motor is shown in Fig. 66. It will be observed that the stator has a continuous polar surface, and that the exciting winding is partially distributed.

The armature is illustrated in Fig. 67, while the complete motor is illustrated in Figs. 322, 323 (pp. 388, 389). Motors of this type are in service on the Lötschberg-Simplon Railway. The locomotives on

* Motors of this type are in operation on the express passenger locomotives of the New Haven Railroad (see Chapter XVII, p. 381).

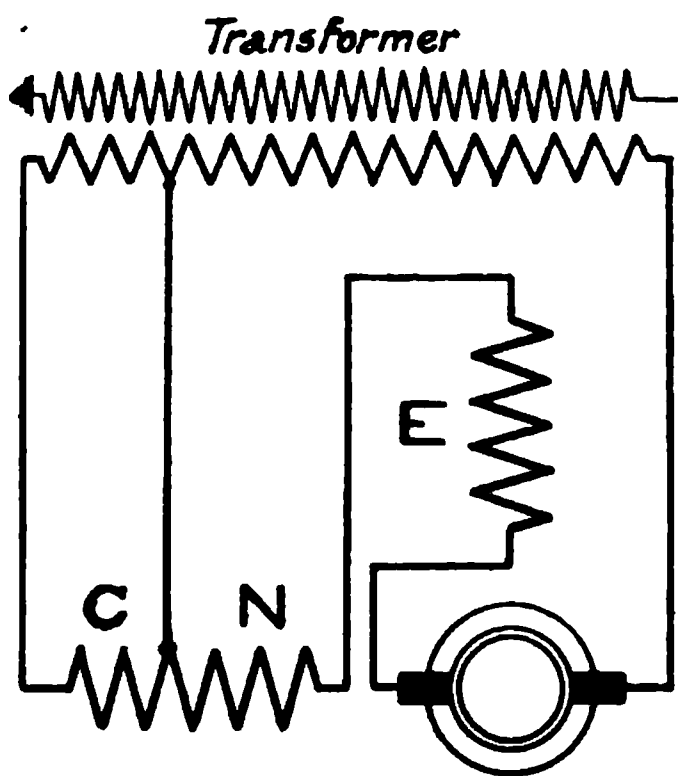


FIG. 70.

this railway (see Chapter XVII) are each equipped with two motors, and each motor is rated at 1250 H.P., 435 volts, 450 r.p.m. (approx.), the rating being on a $1\frac{1}{2}$ -hours basis.

The characteristic curves of the motor are shown in Fig. 68, and

FIG. 71.—Cross-section of Siemens' 180-H.P., 8-Pole, 25-Cycle, Single-phase Series Motor.
(Dimensions in centimetres.)

it should be noted that the efficiency curve includes all losses in the motor and the transmission gear. The characteristic curves of a smaller geared motor, rated at 300 H.P., are shown in Fig. 68a.

The single-phase motors developed by the **Siemens'** Companies are characterised by (1) the special arrangement of the resistance connec-

tions on the armature, (2) the compound (series and shunt) excitation of the commutating poles, and (3) the special manner in which the stator windings are arranged.

Considering the first item, the "resistance connections" are in the form of an auxiliary winding on the armature, and the conductors of this winding are arranged so that the current in them produces a torque. In the ordinary arrangement of resistance connections the conductors of the latter only carry current when in the neutral (or commutating) zone, and, in consequence, no torque is produced by the current in these connections.

The arrangement of the auxiliary winding in the Siemens' motor is shown diagrammatically in Fig. 69. In this diagram the auxiliary winding is shown by the chain-dotted lines, and the main armature winding by the full and dotted lines, the dotted line showing the coil which is short-circuited by the brush, and which is the seat of the transformer-E.M.F. (the latter producing the circulating current in the

FIG. 72a.

FIG. 72b.

direction indicated by the arrows). The arrows on the full lines and the chain-dotted lines represent the direction of the main armature current. It will be noticed that the auxiliary winding covers a pole-pitch in the same way as the armature winding, but is displaced 90 (electrical) degrees from the latter. Thus, when a coil of the armature winding occupies the neutral position, the conductors of the auxiliary winding connected to it are directly under the pole faces, and the interaction of the current in these conductors with the main flux will produce a torque. The path of the circulating current exterior to the coil *ab* (Fig. 69) is through the conductors *Va*, the brush, and the conductors *Vb*. It will be noticed that the direction of this current in the conductors *Va* is opposite to that in the conductors *Vb*, so that the passage of the circulating current through the auxiliary winding does not increase the reactance voltage of the commutated coil.

The conductors of the auxiliary winding consist of copper, and are located in the slots above the main winding (see Fig. 71). The requisite resistance is obtained by increasing the number of turns in the auxiliary winding, the cross-section of the conductors being reduced to the smallest permissible value. In this manner the resistance connections may produce an increase in the torque of as much as 10 per cent. without increasing the size of the armature.

The principles of compound excitation for the commutating poles

have been discussed on pages 59, 60. In practice, the method indicated in Fig. 38 (p. 59) admits of considerable simplification. Thus it is possible to incorporate all the stator windings (viz. the exciting winding, the compensating winding, and the compound commutating-pole winding) into a single winding of the cylindrical (or barrel) type, with all conductors of the same size and shape. The number of conductors and the cross-section of each is chosen, so that, by a series and parallel connection of certain conductors, the correct ampere-turns can be obtained for all the windings.* The shunt winding of the commutating poles is then excited from a tapping on the main transformer, as indicated in Fig. 70.

FIG. 73.—Completely-wound Stator of A.E.G. 6-Pole Compensated-repulsion Motor.

A cross-section of a Siemens motor (of 180 H.P.) with 8 poles is shown in Fig. 71, in which the uniform size and spacing of the stator slots should be noted.

The motor is provided with two exciting windings, one for each direction of rotation. This, however, does not lead to an increase in the copper required, because, if a single exciting winding were adopted, some of the ampere-turns of this winding would be neutralised by the compensating winding. A reference to the diagrams of Fig. 72 will make this clear. In Fig. 72a the neutralising effect of the exciting and compensating windings is shown, while in Fig. 72b the neutralising conductors of Fig. 72a have been replaced by another exciting winding (shown dotted) for the opposite direction of rotation. Thus the total

* In this connection see an article by Dr. Rudolf Richter on "Siemens-Schuckert Alternating-Current Series Motors" (abstracted in *The Electrician*, vol. 58, p. 207).

number of conductors in the stator winding are the same in each case. The provision of two exciting windings enables the control apparatus to be simplified, as the reversing can be effected by the use of two contactors instead of a reverser or four contactors (which would be required for reversing a motor having a single exciting winding).

(2) **Repulsion Motors.**—The constructional features of repulsion motors only differ from those of series motors in the stator winding and the brush gear. It should be noted, however, that the armature voltage

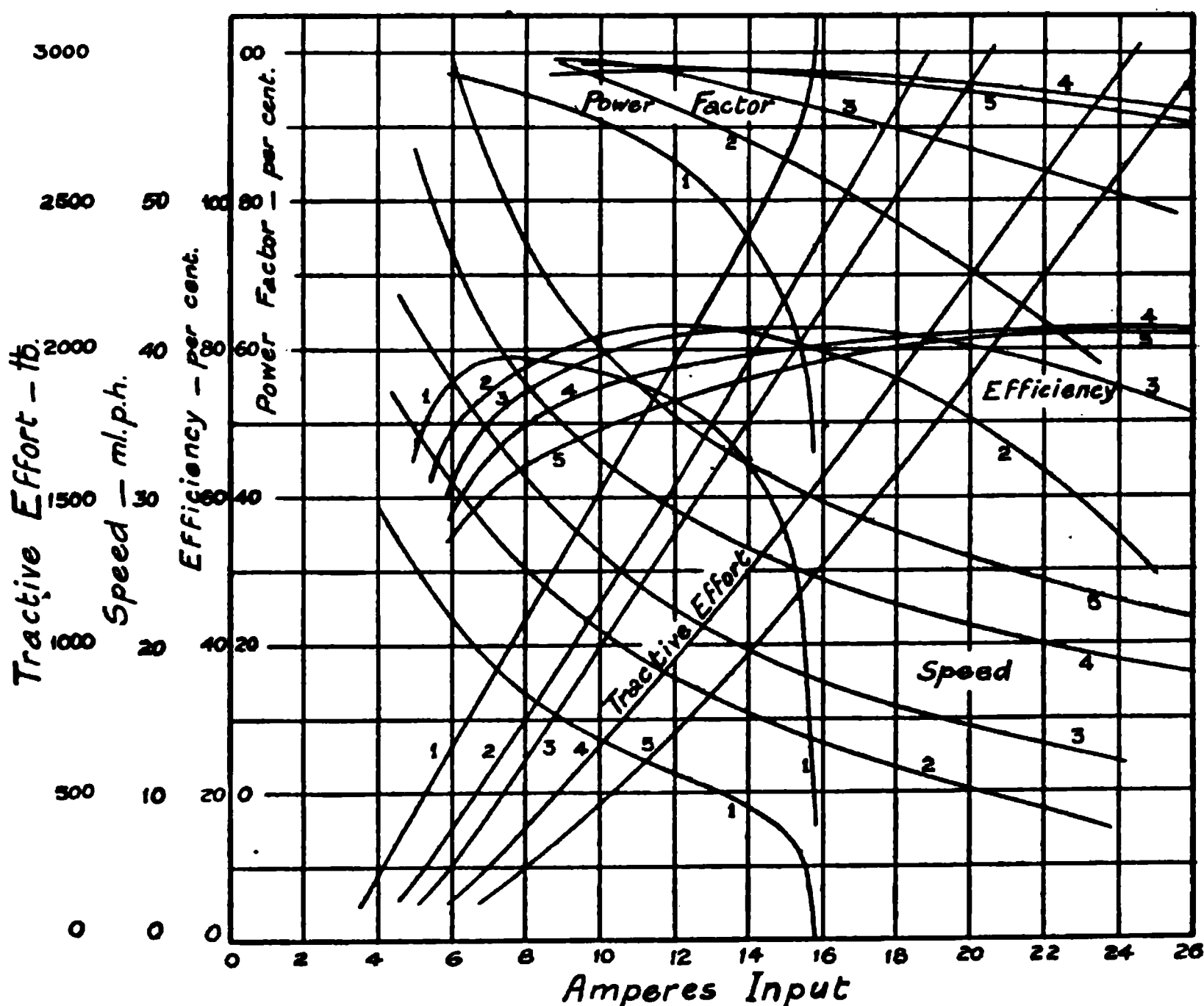


FIG. 74.—Characteristic Curves of 115-H.P., 4-Pole, 25-Cycle, A.E.G. Compensated-repulsion Motor. (43½-in. wheels, 4.24:1 gear ratio). NOTE.—Amperes input refer to the input to the high-tension (6000 volt) side of the transformer.

of a repulsion motor may be selected at such a value that resistance connections are not required.

In the compensated-repulsion motor the stator winding is simply a distributed single-phase winding, with an additional coil located in the centre of two or more pole faces for the purpose of providing a local commutating field at high speeds.

A completely-wound stator for a 200-H.P., 6-pole, **compensated-repulsion motor** (of the A.E.G.) is shown in Fig. 73, in which the location of the commutating coils can be clearly seen. It will be observed that there are three commutating coils, one per pair of poles. The illustration also shows the manner in which the stator laminations are clamped between end-plates, so that the stator core can be removed bodily from the frame. When this method of construction is adopted, the cast-

steel frame is split, in order to facilitate the removal of the stator core.

The brush-gear of a compensated-repulsion motor will comprise (a) the main (or short-circuited) brushes, and (b) the exciter brushes. The main brushes consist of as many brush sets as there are poles, and these sets are permanently short-circuited. The exciter brushes are arranged midway between the main brushes, and the number of sets required will

FIG. 75.—Brown-Boveri-Déri 700-H.P., 10-Pole, 16½-Cycle, Single-phase Motor.

depend on the magnitude of the exciting current and the nature of the armature winding. If a multiple-circuit winding with cross-connected commutator segments is adopted, only two sets of exciter brushes will be necessary.

Typical characteristic curves of a compensated-repulsion motor are given in Fig. 74. These curves refer to the 115-H.P., A.E.G. motors in service on the South London lines of the London, Brighton, and South Coast Railway. The efficiency curves include the gear losses and the losses in the main transformer. The various curves (1–5) refer to the different control notches (see p. 230). On notches 1 and 5 the excitation is reduced by altering the ratio of the exciter transformer.

The principal feature of interest in the Déri (brush-shifting) re-

FIG. 76.—Parts of Brown-Boveri-Déri 90-H.P., 4-Pole, Single-phase Motor.

pulsion motor is the brush-gear, since the stator of this motor closely resembles that of a compensated-repulsion motor. The brushes are arranged in two equal groups—insulated from each other—each group containing as many brush-sets as there are poles. The brush-sets in each group are permanently short-circuited, and the two groups are connected together by a flexible connection. One group of brushes is

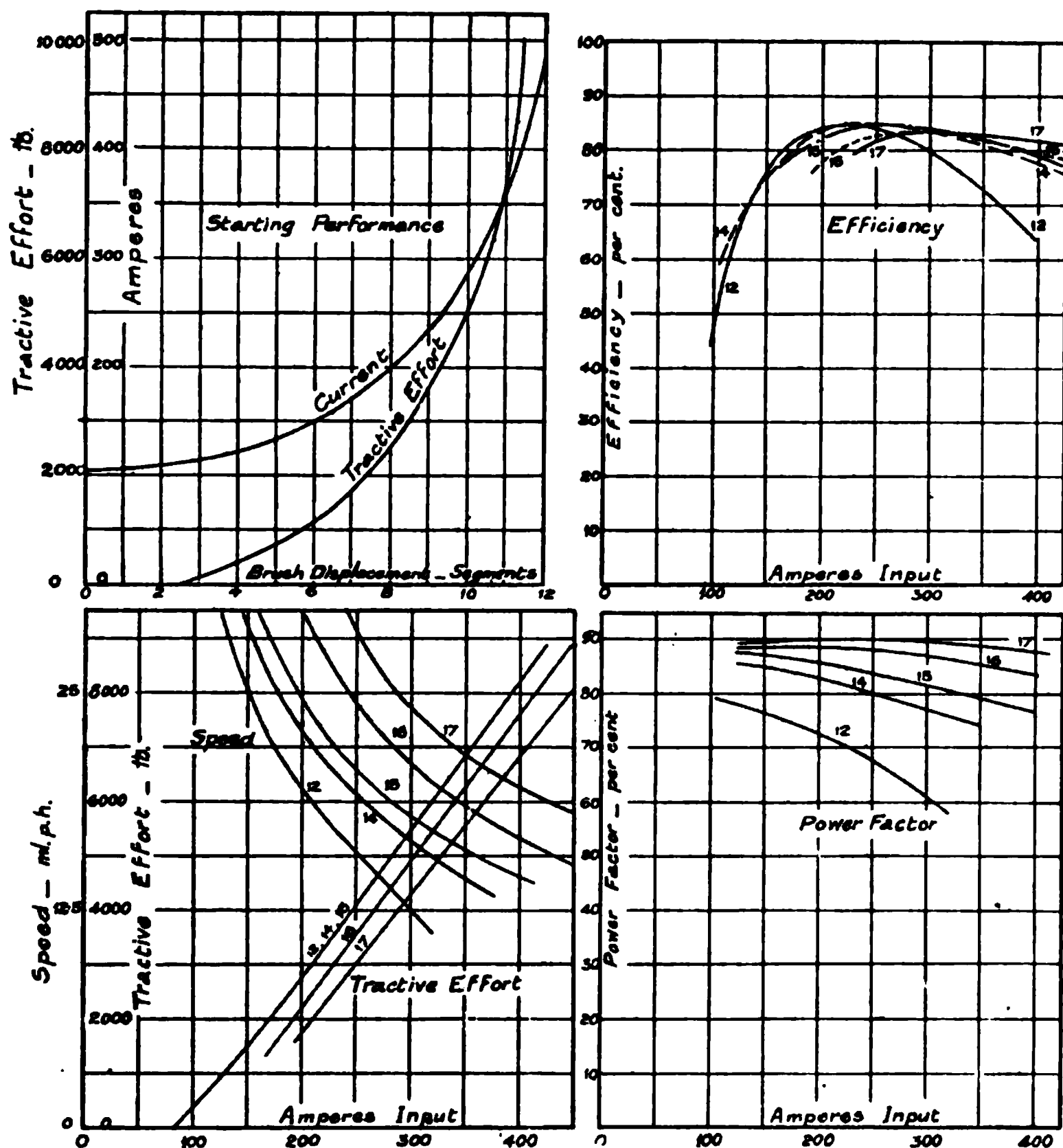


FIG. 77.—Characteristic Curves of Brown-Boveri-Déri Motor, 310 H.P., 12 Poles, 140 r.p.m., 16½ Cycles, 950 Volts. The numbers placed against the speed, tractive-effort, efficiency, and power-factor curves refer to the brush displacement (segments). (Wheels 1070 mm.—42.1 in.—diameter.)

fixed in position, while the other group is arranged to move relatively to it. With traction motors the two groups are arranged to bear upon different parts of the commutator so that the motion of the movable brushes is not restricted by the fixed brushes. The direction of rotation of the armature is then controlled by the direction of movement of the brushes, which is carried out by means of a worm and worm-wheel.

An illustration of a 700-H.P., Brown-Boveri-Déri repulsion motor is shown in Fig. 75. This motor forms part of the equipment of an electric

locomotive (see Chapter XVII, p. 400). The two sets of brushes can be clearly distinguished in the illustration.

The armature, stator, frame-heads, and brush-gear for a smaller geared motor of 90 H.P. are illustrated in Fig. 76.

Typical **characteristic curves** * of a **Déri motor** are given in Fig. 77. These curves refer to a motor—rated at 310 H.P., 950 volts, 140 r.p.m., $16\frac{2}{3}$ cycles—designed for electric locomotives, in which the power is transmitted from the motors to the driving wheels by connecting rods (see Chapter XVII). The starting performance curves included in Fig. 77 are of especial interest, as they show the manner in which the current and tractive-effort (at starting) vary with the brush displacement.

* The author is indebted to Mr. A. C. Eborall and Messrs. Brown, Boveri & Co., for these characteristic curves and the illustrations of Déri repulsion motors.

CHAPTER VI

POLYPHASE TRACTION MOTORS

THE only type of polyphase motor which has been applied to electric traction is the three-phase induction motor.* This motor possesses a "shunt" (or constant-speed) characteristic, and, when speed regulation is required, the regulation can only be obtained *economically* by the use of auxiliary machines or additional windings on the motor. Therefore the polyphase induction motor is entirely unsuitable for suburban services. The machine is, however, suitable for main-line long-distance services, where the stops are infrequent and the acceleration is unimportant. Moreover, with polyphase induction motors, efficient regenerative braking can be obtained without complication of the control apparatus, and therefore these motors are eminently suitable for service on mountain railways. In fact, it is on railways of this nature that the greatest development of the three-phase traction motor has occurred.

The adoption of three-phase motors requires at least two trolley wires (the track rails forming the third conductor), but, in the case of mountain railways, the disadvantages of the duplication of the overhead construction are compensated by the facility with which regenerative braking can be obtained.†

Although the constant-speed type of polyphase motor may be suitable for handling certain classes of traffic, nevertheless, for satisfactory working, it is desirable to provide two or more efficient running speeds. The provision of a number of efficient running speeds will also lead to economy during the starting and accelerating periods.

In practice, the economical methods of regulating the speed of polyphase induction motors are limited, and, for the purpose of discussing these limitations, we will now state the fundamental relations between the speed and torque, as given by the following equations: ‡

* The three-phase variable-speed commutator motor is, at present, in the experimental stage of development. There is no present indication, however, that this machine would be serviceable for suburban service.

The types of polyphase commutators and their characteristics are discussed very fully by Mr. N. Shuttleworth in a paper on "Polyphase Commutator Motors" (*Journal of the Institution of Electrical Engineers*, vol. 53, p. 439).

† Regenerative braking is also possible with single-phase commutator motors—as explained in Chapter XII—but this entails additional windings and control apparatus; while the results obtained are, in general, inferior to those obtained with three-phase motors.

‡ For the deduction of these equations, the student is referred to standard text-books.

$$(1) \text{ Speed : } n = \frac{120f}{p}(1-s) \quad (21)$$

$$(2) \text{ Torque : } M = \frac{K\Phi^2 s R_2^*}{R_2^2 + (sX_2)^2} \quad (22)$$

$$(3) \text{ Slip : } s = \frac{f-f_1}{f} \quad (23)$$

where n is the speed of the rotor in revolutions per minute,

f the frequency of the supply current,

f_1 the frequency of the rotor current,

p the number of poles,

s the slip,

M the torque exerted by the rotor,

K a constant,

Φ the flux per pole,

R_2 the resistance per phase of the rotor,

X_2 the reactance per phase of the rotor.

For a given motor the torque equation corresponding to starting conditions ($s=1$) may be written

$$M = \frac{K\Phi^2 R_2}{Z^2}, \quad (22a)$$

where Z is the total impedance of the motor; while for running conditions the equation becomes, approximately,

$$M = \frac{K\Phi^2 s}{R_2}, \quad (22b)$$

$$\text{from which we obtain } s = \frac{R_2 M}{K\Phi^2} \quad (23a)$$

Considering only supply systems of constant frequency, it is apparent from equation (21) that there are **two methods of regulating the speed of an induction motor**, viz. (1) by varying the slip, (2) by changing the number of poles. The speed variation obtained by the separate use of either of these methods is limited, but, by the combination of the two methods, a large speed variation can be obtained. Thus, in the first method, the maximum speed is obviously limited by the synchronous speed ($120f/p$); while, in the second method, the motor will possess a constant-speed characteristic for each set of poles, and intermediate speeds will have to be obtained by varying the slip.

Now equation (23a) shows that, for constant torque, the slip is directly proportional to the resistance of the rotor circuit and inversely proportional to the square of the flux. In a motor operating on a constant voltage circuit, the flux will be practically constant, and the voltage induced in the rotor will be proportional to the slip, while for constant torque the rotor current will be practically constant. Hence it follows that the electrical power developed in the rotor will be directly proportional to the slip. A large slip, therefore, will correspond to the expenditure of a large amount of energy (called the "slip energy") in the rotor circuit; and if the slip has been obtained by the insertion of rheostats in this circuit, then it is apparent that the energy due to the increased slip will be wasted in the rheostats.

* Neglecting the resistance and reactance of the stator circuit.

It is not necessary, for the purpose of obtaining a large slip, that this energy should be wasted in rheostats, as it can be utilised in the form of mechanical or electrical energy by means of (1) another induction motor connected in cascade with the motor to be regulated, (2) a commutator motor, or (3) a rotary converter combined with a motor-generator set. In each of these systems the slip energy must be delivered either to the supply system or to the shaft of the main induction motor. Although each system has been applied to industrial plants, only the cascade system has been applied to railway motors, and the principal developments in this direction have occurred on the Continent.

The **cascade connection** of the main motor (the speed of which is to be regulated) with another induction motor (called the secondary motor) requires the two rotors to be mechanically coupled or geared together. For example, the rotors may be mounted on the same shaft

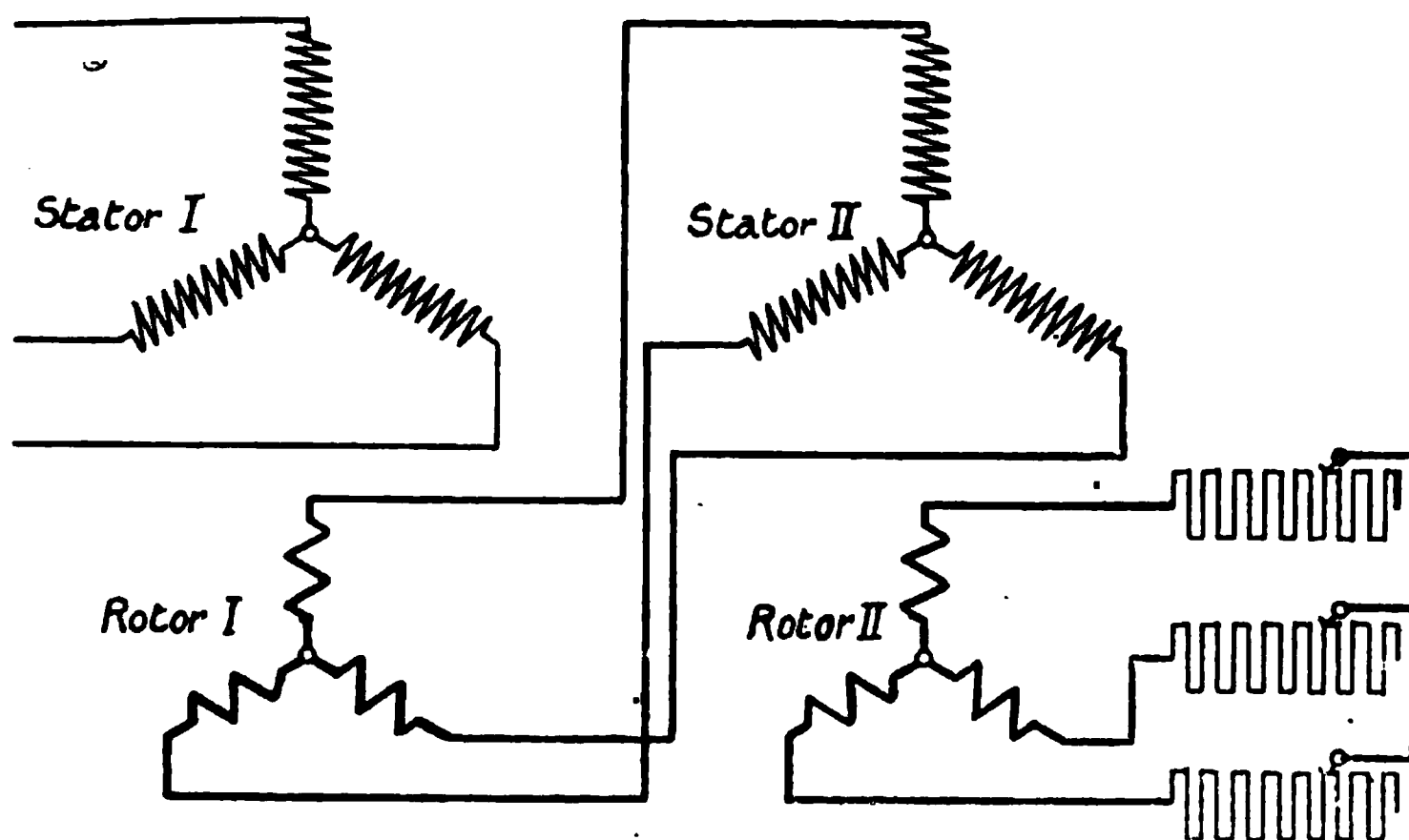


FIG. 78.

or on separate shafts, but in the latter case the shafts must be geared or mechanically connected together. The rotor of the main motor must be wound for the same number of poles as the stator, and must be provided with slip rings, while the rotor of the secondary motor may be of a similar type, or of the squirrel-cage type.

In the cascade connection the stator winding of the main motor is connected to the supply. The slip-rings are connected to the stator winding of the secondary motor, and the rotor winding of this motor is connected to a rheostat, as indicated in Fig. 78.* The rheostat enables the speed of the set to be regulated up to the cascade synchronous speed, and it can be shown that, if each motor has the same number of poles, the cascade synchronous speed is one-half of the synchronous speed of the main motor.

Thus consider the set running light, with the rotor of the secondary

* It is not essential that the rotor of the main motor be connected to the stator of the secondary motor, as the two rotor windings may be connected together and the rheostats connected to the stator winding of the secondary motor. If the secondary motor is provided with a squirrel cage rotor, its stator winding will have to be supplied from the rotor of the main motor, and, at starting, the voltage applied to the stator of the main motor will have to be reduced.

motor short-circuited, and let p_1 , p_2 respectively denote the number of poles in the main and secondary motors. Then, if f is the frequency of the supply system and s is the slip in the main motor corresponding to cascade synchronous speed, the speed of the main motor will be $\frac{f}{\frac{1}{2}p_1}(1-s)$ revolutions per second. The frequency supplied to the secondary motor will be fs , and therefore the synchronous speed of this motor will be $\frac{fs}{\frac{1}{2}p_2}$ revolutions per second.

Since the two rotors are mechanically coupled together, the ratio.

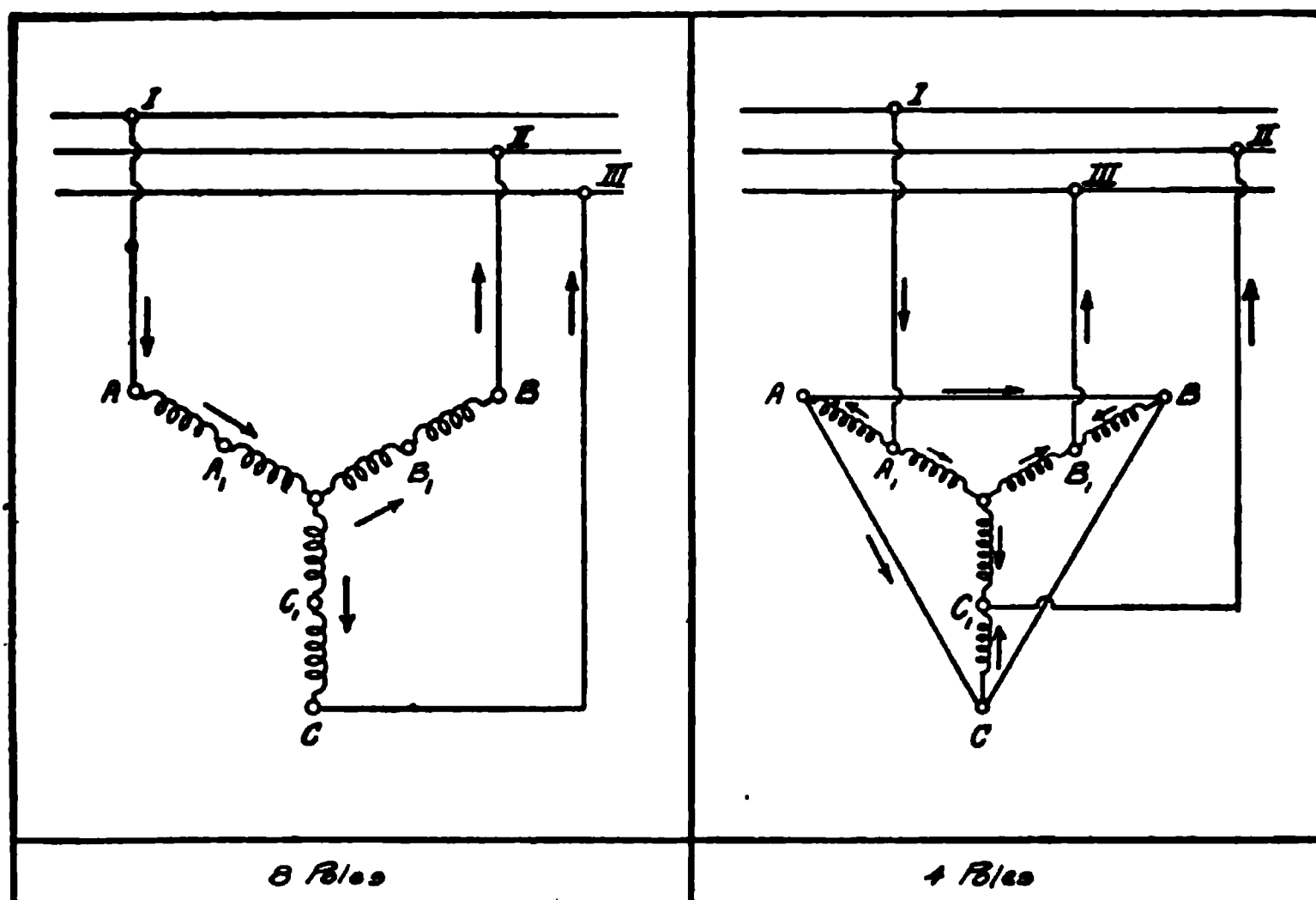


FIG. 79.—Simplest Method of arranging a Three-phase Winding for Pole-changing.

of their speeds will be constant, and, if we assume that both rotors are fixed to the same shaft, then $\frac{fs}{\frac{1}{2}p_2} = \frac{f}{\frac{1}{2}p_1}(1-s)$, whence $s = \frac{p_2}{p_1 + p_2}$. If each motor has the same number of poles, the minimum slip of the main motor cannot have a value less than 50 per cent., i.e. the cascade synchronous speed is one-half of the synchronous speed of the main motor. Generally the cascade synchronous speed may be written as

$$n(\text{r.p.m.}) = \frac{120f}{p_1} \left(1 - \frac{p_2}{p_1 + p_2} \right) = \frac{120f}{p_1 + p_2} * \dots \dots \dots (24)$$

It is possible, therefore, to obtain two economical speeds, but intermediate speeds will have to be obtained by regulating the slip by means

* In deriving this equation, we have tacitly assumed that the direction of rotation of the main and secondary motors (when supplied separately) is the same. If the secondary motor is connected so that it tends to rotate in the opposite direction to the main motor, the motors are said to be connected in "differential cascade," and the synchronous speed under these conditions will be given by

$$n(\text{r.p.m.}) = \frac{120f}{p_1 - p_2}.$$

of rheostats. If, however, both motors are wound with pole-changing windings (see p. 110), a larger number of economical speeds can be obtained.

The principal objections to speed regulation by the cascade system are: (1) two motors are required,* which, if they are to operate in parallel (at speeds between cascade synchronous speed and full speed), must have the same number of poles, while the stator windings of the

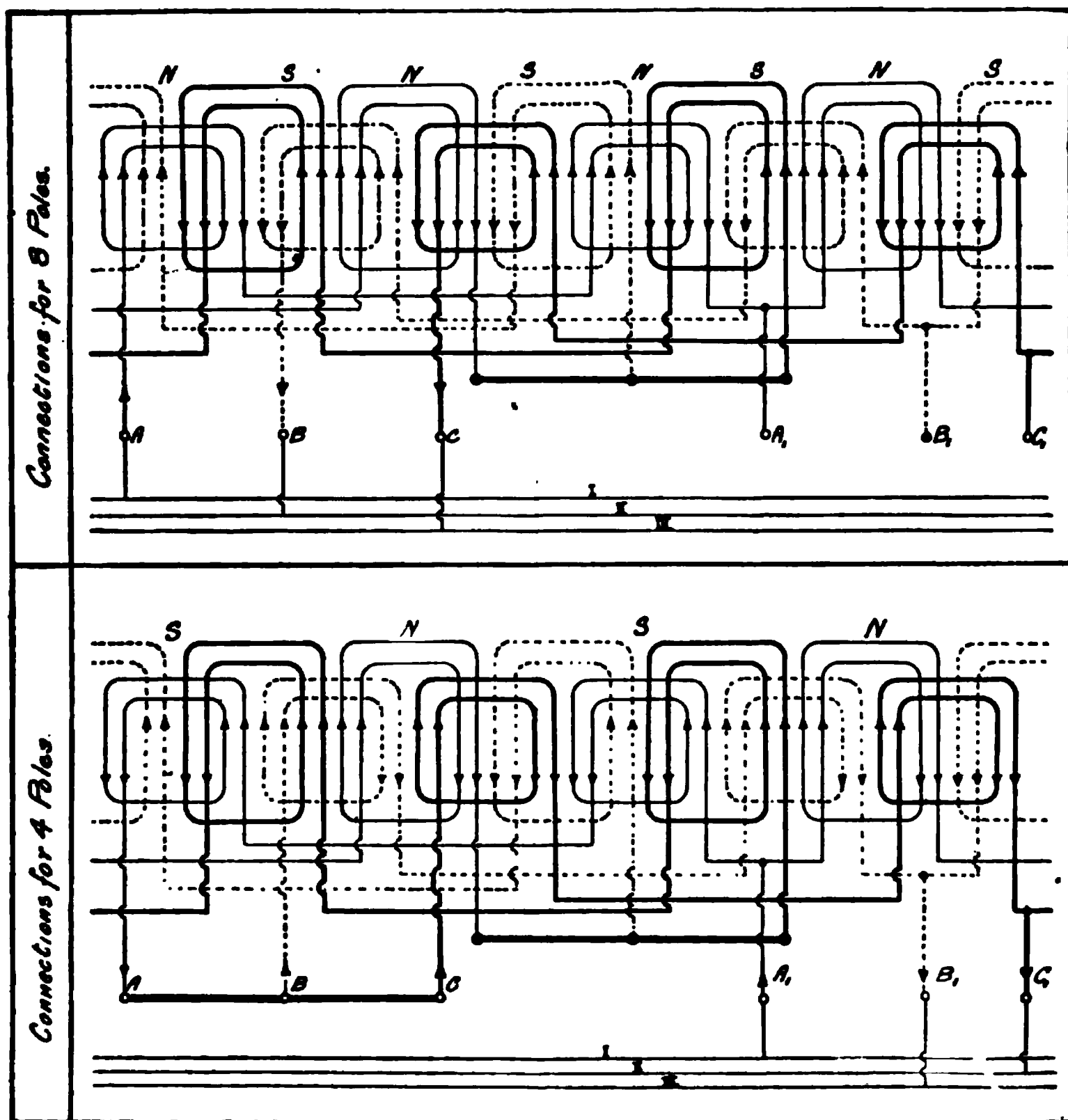


FIG. 80.—Connections and Development of Three-phase Winding for Pole-changing according to method of Fig. 79.

secondary motor must be designed to operate with the full supply voltage and also with the rotor voltage (corresponding to cascade synchronous speed) of the main motor; (2) the low power-factor of the combination, which, even for motors of good electrical design, seldom exceeds 80 per cent.:

It is not essential that the two motors should have separate frames,

* In some special cases the two motors can be combined into one. Motors of this type (known as the "Hunt Cascade Motor"), however, have only been developed for industrial service. See "Electric Motors," Hobart, p. 574; also *Journal of the Institution of Electrical Engineers*, vol. 39, p. 648; vol. 52, p. 406.

as, when the rotors are mounted on the same shaft, the two stators may be combined in a common frame.*

The low power-factor is due to the magnetising current of the secondary motor being superimposed on that of the main motor, and, to obtain a power-factor as high as the value given above, it is necessary to design each motor for a low magnetising current and low reactance, the attainment of which is facilitated by adopting a low frequency of supply. For example, on the Italian State Railways, where the cascade system has been largely developed, frequencies of 15 and 16½ have been adopted.

The method of regulating the speed of polyphase motors by changing the number of poles has been developed for electric railway work by Messrs. Brown, Boveri & Co., and by the Società Italiana

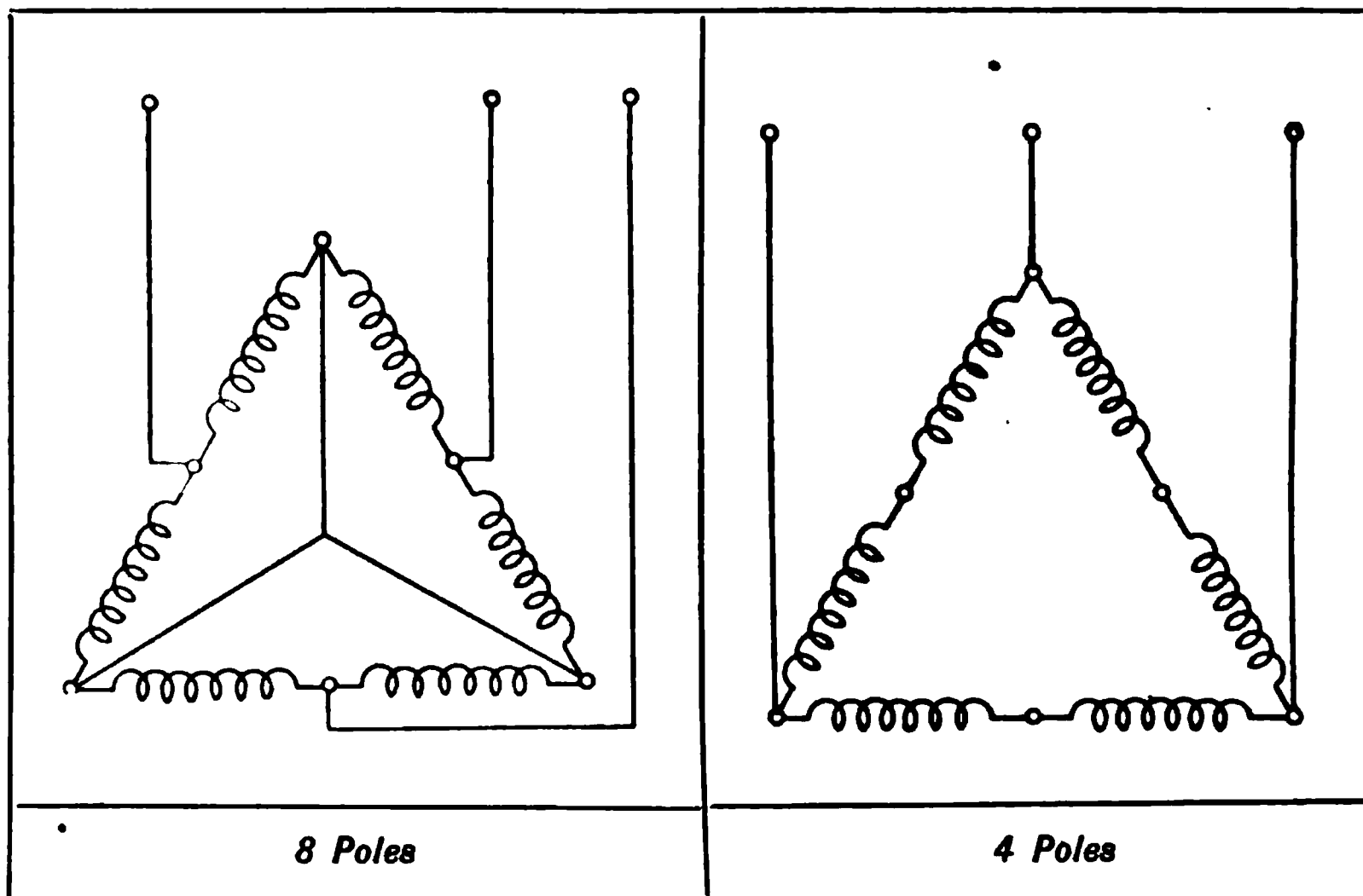


FIG. 81.—Alternative Method of arranging Three-phase Winding for Pole-changing.

Westinghouse. This method is used on the locomotives supplied by these firms to the Italian State Railways, and was adopted on the Simplon Tunnel locomotives manufactured by Messrs. Brown, Boveri. In some recent locomotives supplied to the Italian railways the motors have been arranged for four speeds, two being obtained by cascade control, and two by changing the number of poles. Generally speed variation by changing the number of poles is limited to two or four synchronous speeds, the latter number being obtained by the use of two separate windings on the stator, connected so that the poles may be changed in the ratio of 2 : 1. In this case the rotor is usually of the squirrel-cage type, and starting is performed by varying the voltage applied to the stator.

When the number of poles is required to be changed in the ratio of

* As developed by Ganz & Co. for electric locomotives. See "Electric Motors," Hobart, Figs. 610, 611 (p. 568).

2 : 1, it is only necessary to bring out tappings from the centre point of each phase of the stator winding. The larger number of poles are obtained by connecting the supply lines to the ends of the stator winding in the ordinary way, but for the smaller number of poles the tappings are connected to the supply lines, and the ends of the phases are short-circuited, as indicated diagrammatically in Fig. 79.*

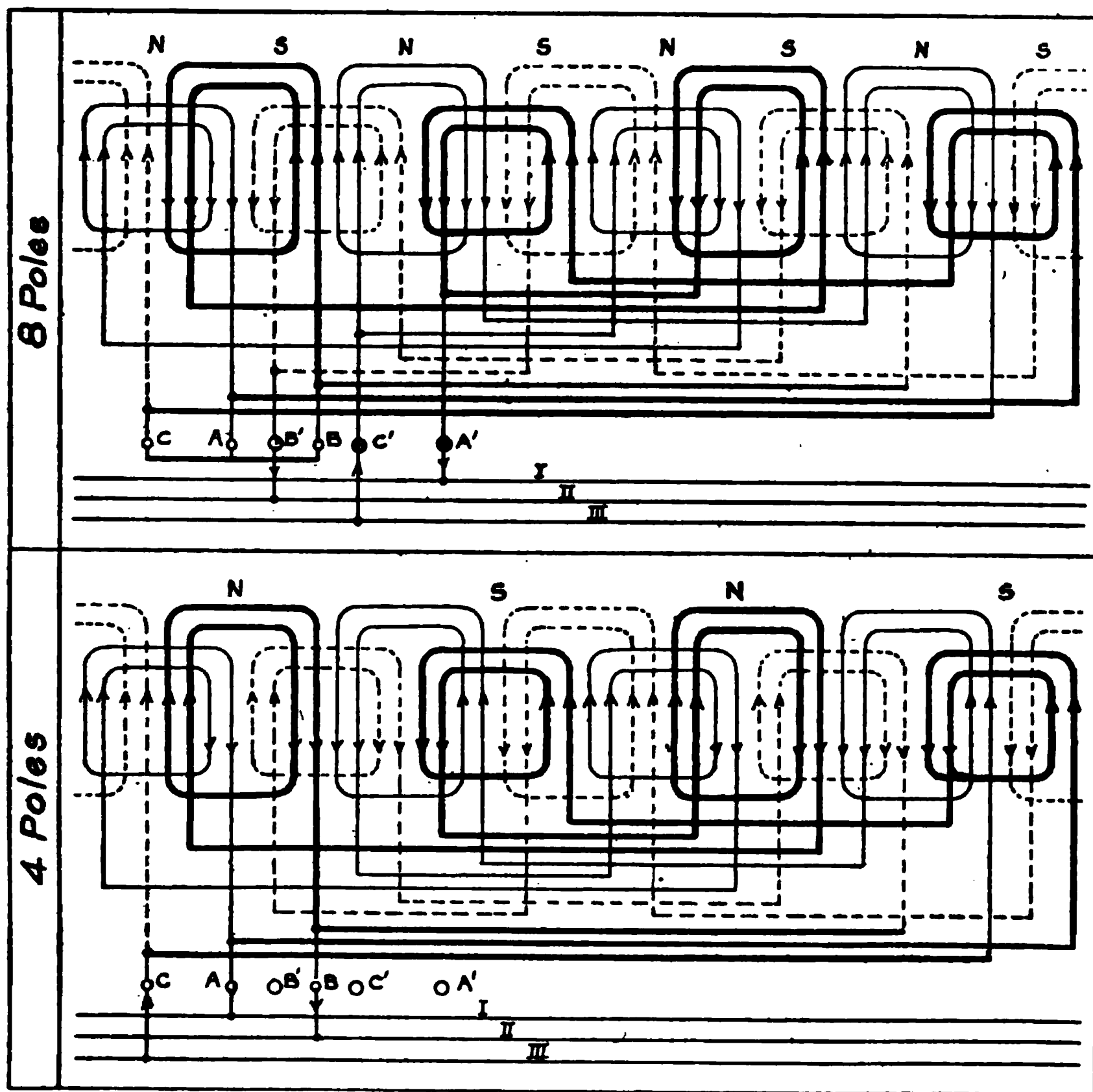


FIG. 82.—Connections and Development of Three-phase Winding for Pole-changing according to method of Fig. 81.

The development of a three-phase 8-pole winding, showing the polarities for each of these combinations, is given in Fig. 80. In order that the direction of rotation shall not be reversed when the winding is connected for four poles, two of the phases must be reversed in relation to the line wires (see Figs. 79, 80). If, however, the winding is star-connected for the larger number of poles and Δ -connected for the smaller number of poles—as shown in Figs. 81, 82—this reversal of the line wires is unnecessary.

* This method is generally adopted when pole-changing is required with stationary motors.

The connections shown in Fig. 81 have been adopted by Messrs. Brown, Boveri & Co. for the motors on the Simplon Tunnel locomotives, to which reference will be made later. Each phase of the stator winding is divided into two equal sections—the ends of each section being re-

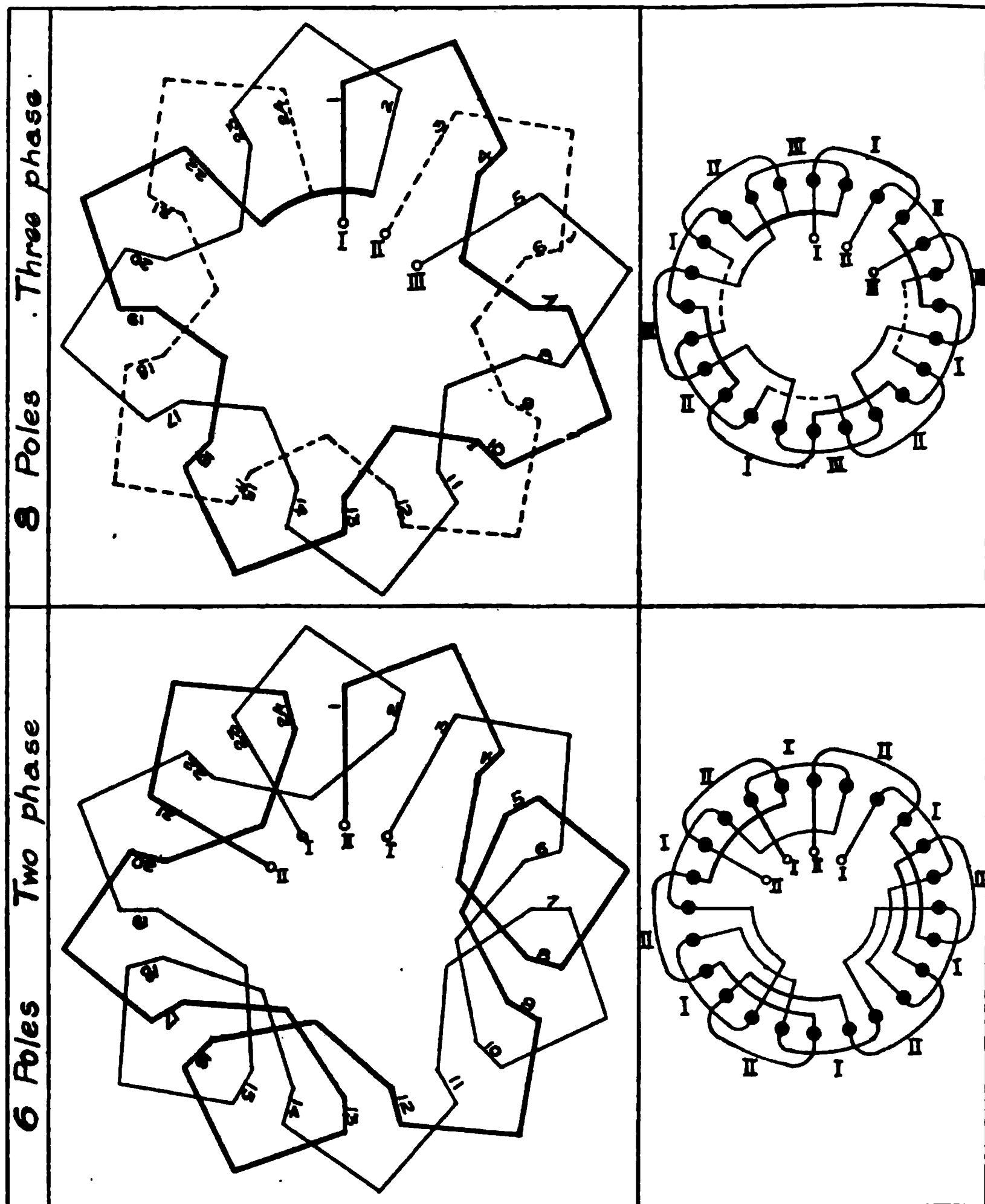


FIG. 83.

FIG. 83a.

Connections of Pole-changing Winding to give 8 Poles, Three-phase, and 6 Poles, Two-phase.

versed in connecting up—and the phases are connected to form a closed winding, from which tappings are brought out at the six junctions, as indicated in Fig. 82 (which shows the principle applied to an 8-pole winding). The tappings are connected to a controller (see Fig. 221), by means of which the combinations shown in Fig. 81 are obtained.

It will be observed that in the Δ -connection the sections of each phase are in series and the current is led into the winding at the junctions between the phases, while in the star-connection the sections of each phase are in parallel, the current being led into the winding at the mid-point tappings. Therefore, in the latter case, the current in the two sections of each phase will flow in opposite directions, and, since the sections are reversed in connecting up, the result will be the full number of poles for which the winding is designed.

A reference to Figs. 80, 82 will show that, with the connections for the smaller number of poles, certain parts of the stator winding neutralise one another. For the winding shown in these diagrams it will be found that one-third of the total number of conductors are inactive. Hence, instead of the active turns per phase being reduced in the ratio of $T : \frac{1}{2}T$ (i.e. in the same ratio as the poles), they are reduced in the ratio of $T : \frac{1}{2}T - \frac{1}{3}T$, or $T : \frac{1}{3}T$, where T denotes the number of turns in series per phase. Therefore, with the connections of Fig. 79, and the same line voltage in each case, the flux per pole corresponding to the smaller number of poles will be three times that for the larger number of poles. As the area of the pole face at the air-gap is doubled when the number of poles is halved, it follows that the flux-density in the air-gap will only be increased by 50 per cent. The cross-section of the stator and rotor cores, however, are the same in each case, and to avoid excessive flux-density and heating, the cross-section of the cores must be designed for the smaller number of poles.

It will be of interest to compare the **magnetising currents** for the two cases. If the reluctance of the iron portion of the magnetic circuit be neglected, the magnetising current of a three-phase induction motor is given by:— *

$$i_m = \frac{0.22\Delta B_m}{T/\frac{1}{2}p} = \frac{0.11\Delta B_m}{T/p} \quad \dots \dots \dots (25)$$

where i_m is the R.M.S. magnetising current in amperes,

Δ the length of the air-gap in inches,

B_m the maximum value of the flux-density (lines per sq. in.) in the air-gap,

T the turns in series per phase,

p the number of poles.

This equation shows that the magnetising current will be directly proportional to the flux-density in the air-gap, and inversely proportional to the turns per pole per phase (i.e. T/p). Hence, if i_m, B_m, T refer to the machine when connected with the larger number of poles ($=p$), and i'_m, B'_m, T' refer to the machine when connected for one-half of this number of poles, then

$$\frac{i_m}{i'_m} = \frac{B_m}{T/p} \div \frac{B'_m}{T'/p/2} = \frac{B_m}{B'_m} \cdot \frac{2T'}{T}.$$

Now

$$B'_m = 1.5 B_m, \text{ and } T' = \frac{1}{3}T,$$

therefore

$$\frac{i_m}{i'_m} = \frac{2 \times 0.33}{1.5}, \text{ whence } i'_m = 2.25 i_m.$$

* The resultant ampere-turns per pair of poles per phase $= 2i_m T$, which ampere-turns are expended over the double air-gap. Hence

$$\frac{B_m}{\sqrt{2}} = \frac{0.4\pi}{2\Delta} \times \frac{6.45}{2.54} \times 2i_m \frac{T}{p/2} = 3.19 \frac{i_m T}{\Delta p/2}, \text{ or } i_m = \frac{0.22\Delta B_m}{T/\frac{1}{2}p}.$$

Let us see how this result compares with that for the method of connection shown in Fig. 81. If E is the line voltage, then the voltage per phase for the star-connection is $\frac{E}{\sqrt{3}}$, and the turns in series per phase

are $\frac{1}{2}T$; while, for the Δ -connection, the voltage per phase is E , and the effective turns in series per phase are $T' = (T - \frac{1}{3}T) = \frac{2}{3}T$ (since one-third of the winding is inactive, as shown above). Hence the flux in the second case (corresponding to the smaller number of poles) will be

$$\Phi' = \Phi \frac{E}{\frac{2}{3}T} \div \frac{E}{\frac{1}{2}T\sqrt{3}} = 1.3\Phi$$

(Φ being the flux per pole corresponding to the larger number of poles).

Hence $B'_m = \frac{1.3}{2}B_m$. Therefore $\frac{i'_m}{i_m} = \frac{2}{1.3} \times \frac{4 \times 2}{3} = 4.1$, whence $i'_m = 0.24i_m$.

It is apparent that this method of connection (Fig. 81) is preferable to that in Fig. 79, especially for railway motors, as, when the motor is running with the smaller number of poles, the flux-density in the stator core is not very different from that under normal conditions (i.e. with the full number of poles), the relative densities being 1.3 : 1 respectively. With the method of connection shown in Fig. 79 the relative densities would be 3 : 1, if the supply voltage were the same in each case. Hence the stator core for the former method of connection (Fig. 81) can be made smaller in external diameter and lighter than that for the latter method (Fig. 79), assuming other features of the design to be identical.

The influence of the number of poles on the torque of a changeable pole motor is shown by the following expression * :—

$$M = K \frac{wp}{f(1-s)}, \quad \dots \dots \dots (26)$$

where w is the total I^2R loss in the rotor circuit, and M , K , p , f , s have the same significance as above (p. 102).

Stator and rotor windings for combined pole-changing and cascade methods of speed regulation.—The above discussion on changeable-pole motors has been confined to windings in which the number of poles are changed in the ratio of 2 : 1. In some cases, however—particularly where the pole-changing and cascade methods of speed regulation are combined—it is desirable to be able to change the poles in a smaller ratio than 2 : 1. For instance, four running speeds, in the ratio of 1 : 1.33 : 2 : 2.66 (or 1 : 1.5 : 2 : 3) will be more suitable for general railway service than four running speeds in the ratio of 1 : 2 : 3 : 4. Now, if four synchronous speeds, in the ratio of 1 : 1.33 : 2 : 2.66 are to

* The total power developed by the rotor $= 2\pi nM \times \frac{746}{33,000}$ watts, which is equal to the total I^2R loss (w) in the rotor. Substituting for n from equation (21) we obtain

$$w = 2\pi \frac{120f}{p} (1-s) M \times \frac{746}{33,000};$$

whence

$$M = \frac{wp}{f(1-s)} \times \frac{33,000}{2\pi \times 120 \times 746},$$

or

$$M = K \frac{wp}{f(1-s)}.$$

be obtained by the combination of pole-changing and cascade control, then obviously the stator and rotor windings of each motor must be

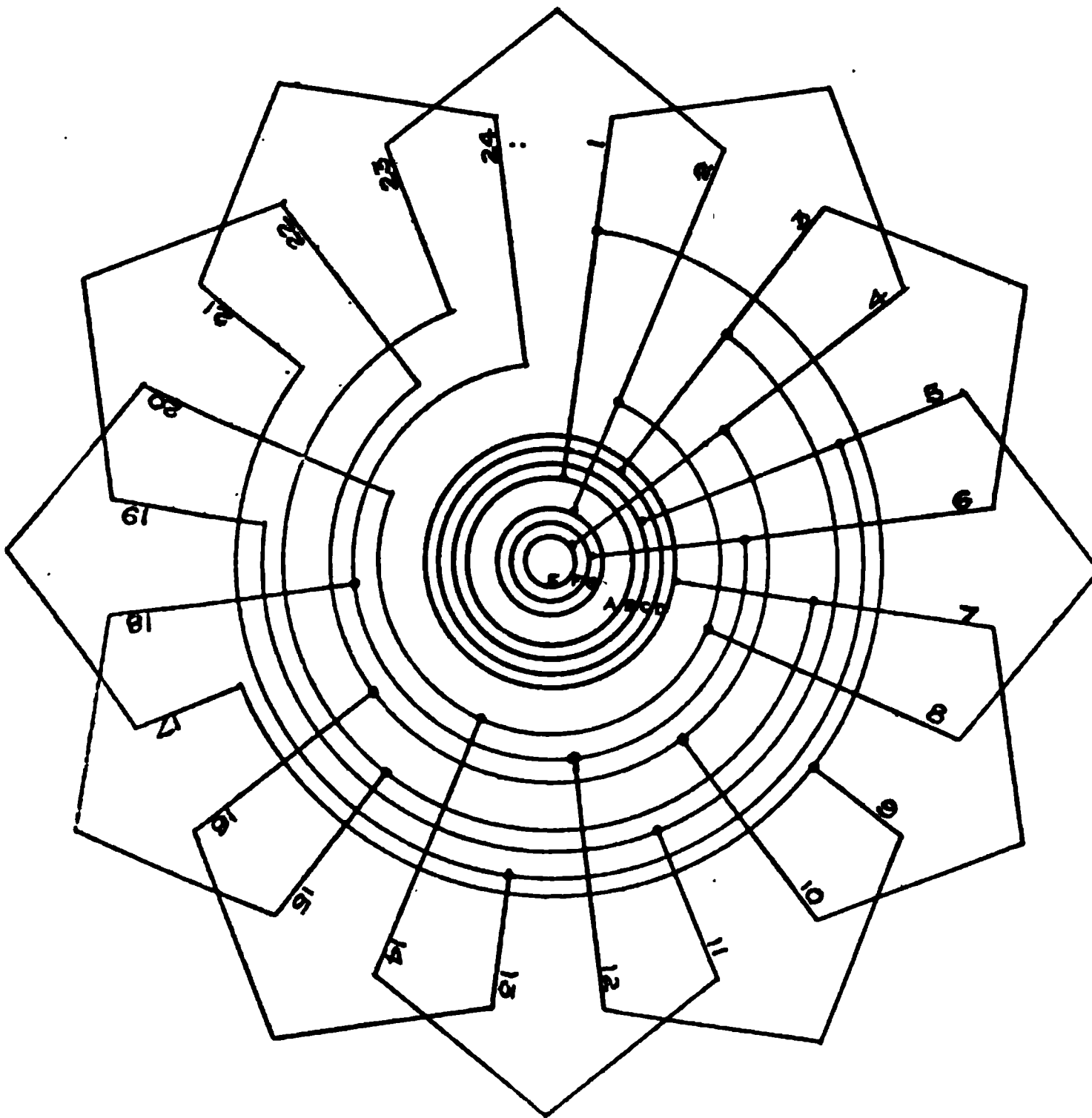


FIG. 84.—Connections of Rotor Winding suitable for the Pole-changing Stator Winding of Fig. 83.

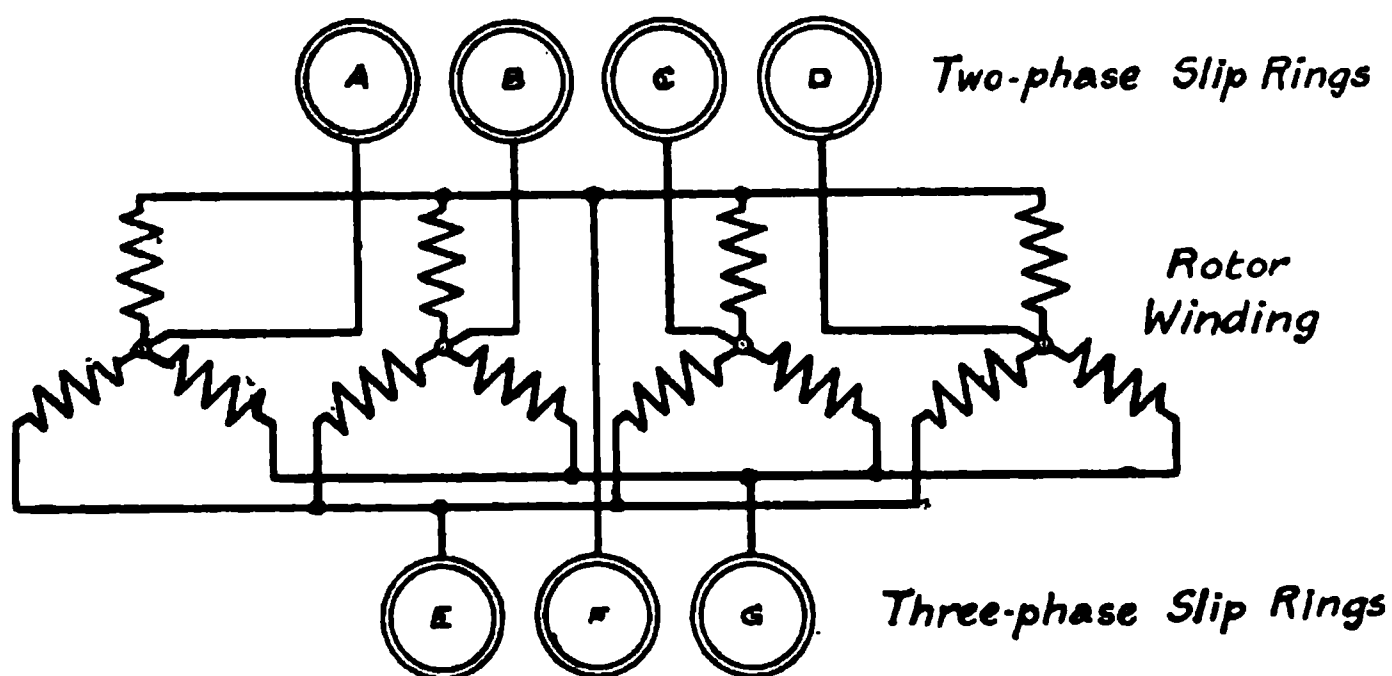


FIG. 84a.—Diagram of Circuits for the Winding shown in Fig. 84.

such that two groups of poles—in the ratio of 1 : 1.33—can be obtained. A cursory consideration of the problem would result in the provision

of two sets of stator and rotor windings on each motor. The performance of such motors would not be very notable, while the duplication of the control apparatus would result in an undesirable increase in the weight and maintenance of the equipment.

The problem, however, admits of a more satisfactory solution, and it is possible to obtain the required speed variation, with satisfactory performance at all speeds, by means of a *single winding on each stator and rotor*. The stator winding will, of course, require a pole-changing switch, and the single rotor winding will require two sets of slip-rings. The manner in which this result is obtained is extremely interesting, and a practicable application of the method is found in the equipments for the four-speed passenger locomotives built by the **Società Italiana Westinghouse** for the Italian State Railways.*

Let us consider that the poles are to be changed in the ratio of 8 : 6. Now an examination of an 8-pole three-phase full-pitch winding will

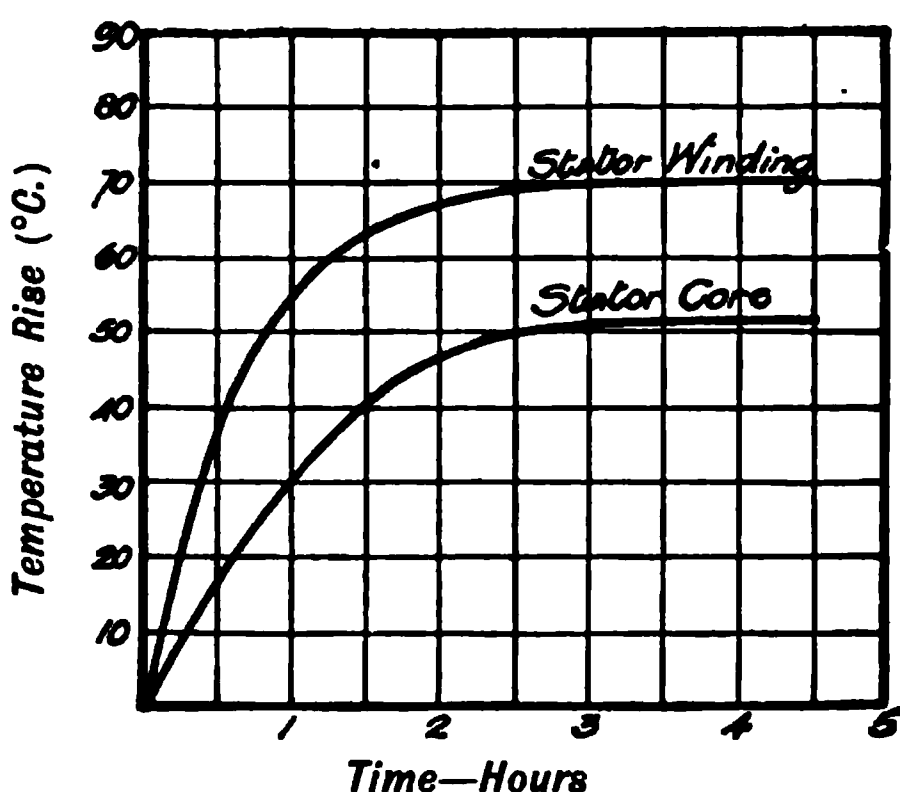


FIG. 85.—Results of Heat-run on 220-H.P., 12/6-Poles, 25-Cycle, Brown-Boveri Railway Motor (6-Pole Winding).

show that, for six poles, the coils will span 75 per cent. of the pole pitch corresponding to the smaller number of poles. But this 8-pole winding cannot be converted into a 6-pole three-phase winding by using the same coils. It may, however, be converted into a 6-pole *two-phase* winding by simply interchanging the connections between the coils, in the manner shown in Fig. 83. The conversion is shown better in the diagram of Fig. 83a, which represents the relative positions of the coils in the stator, and also their phase relations, for the three-phase and two-phase connections. The two-phase winding may be supplied

from the three-phase system by means of two “T-connected” auto-transformers, as described in Chapter XI (p. 252).

Let us now turn our attention to the rotor winding. Obviously this must be suitable for either six or eight poles. Since cascade working is to be adopted, the rotor winding must be capable of supplying both three-phase and two-phase current, viz. three-phase current with eight poles, and two-phase current with six poles. Although these requirements may appear to be rather onerous for a single winding, nevertheless a single winding can be arranged to fulfil them. Thus, instead of the usual star-connected three-phase rotor winding generally adopted, we may use four star-connected three-phase windings connected permanently in parallel, as shown in Fig. 84. This winding is wound with the same number of conductors as the usual winding, and the three common ends of the windings are connected to one set of three slip-rings, while the four neutral points are connected to another set of four slip-rings. These connections will be clear from an inspection of Fig. 84a.

* See Chapter XVII for a description of these locomotives.

The voltage relations will now be investigated. Let $3T$ denote the total number of turns in the stator winding, and Φ_3, Φ_2 denote respectively the fluxes corresponding to a terminal voltage V in each case. Then the turns in series per phase will be T for the three-phase 8-pole connection, and $\frac{3T}{2}$ for the two-phase 6-pole connection. If the breadth coefficients for the 8-pole and the 6-pole windings be assumed as 0.96 and 0.9 respectively, then we must have

$$\frac{V}{\sqrt{3}} = 4.44 \times 0.96 \Phi_3 T f \times 10^{-2},$$

and
$$V = 4.44 \times 0.9 \times 0.92 \Phi_2 \frac{3T}{2} f \times 10^{-2}, *$$

whence
$$\Phi_2 = 1.34 \Phi_3.$$

For equal fluxes in two-phase and three-phase working the terminal voltage for the 6-pole winding must therefore be 0.75 of the normal three-phase line voltage. This voltage can readily be obtained from the auto-transformer.

Let T' denote the total number of turns in the rotor winding; then there are $\frac{T'}{12}$ turns in series per phase for three-phase working, and $\frac{T'}{6}$ turns in series per phase for two-phase working. Hence, with equal fluxes (Φ), and assuming the same breadth coefficients as above, the voltage (V_3) between the three-phase slip-rings is

$$V_3 = \sqrt{3} \times 4.44 \times 0.96 \times \Phi \times \frac{T'}{12} \times f' \times 10^{-2},$$

and the voltage (V_2) between the two-phase slip-rings is

$$V_2 = 4.44 \times 0.9 \times 0.92 \times \Phi \times \frac{T'}{6} \times f' \times 10^{-2},$$

whence $V_2 = V_3$. Thus cascade working will be practicable for both sets of poles.

General considerations relating to three-phase traction motors.

The principal considerations—other than those for obtaining speed variation—in the design of three-phase motors for traction service are: (1) the leakage factor, (2) the air-gap, (3) the ventilation (as affecting the temperature rise).

The **air-gap** affects the leakage factor, which, in turn, affects the power-factor and the overload capacity. Now, the leakage factor or dispersion coefficient (σ) is usually defined as the ratio of the magnetising current to the ideal short-circuit current (at normal voltage); and, by means of the Heyland (or circle) diagram, it can be shown that the maximum power-factor (PF_m) is given by $PF_m = \frac{1-\sigma}{1+\sigma}$; while the over-

load capacity (ξ) $= \frac{1+\sigma}{2\sqrt{\sigma}}$. Hence, in the interests of a high power-factor and large overload capacity, the leakage factor must be small.

* The term 0.92 is introduced to allow for the fractional pitch of the two-phase winding. In this connection see *Transactions of the American Institute of Electrical Engineers*, vol. 26, p. 1485 (Paper on "Fractional-pitch Windings for Induction Motors," by Prof. C. A. Adams).

FIG. 86.—Stator of Westinghouse 410-H.P., 8/4 Poles, 25-Cycle, Three-phase Railway Motor.

FIG. 87.—Rotor of Westinghouse 410-H.P., 8/4-Poles, 25-Cycle, Three-phase Railway Motor.

The factors which influence the magnetising current have already been discussed. The ideal short-circuit current is determined from considerations of the leakage reactance of the windings, which is usually estimated from empirical formulæ.* The leakage factor may, however, be estimated directly from the formulæ of Hobart† and Behn-Eschenburg.‡ These formulæ have been obtained from test results on stationary motors and may require modification when applied to traction motors, as the

FIG. 88.—Società Italiana Westinghouse 1300-H.P., 8/6-Poles, 16½-Cycle, Three-phase Railway Motor. NOTE.—This motor forms the secondary motor for cascade working. The pole-changing, re-grouping, and change-over switches are mounted on the frame of the motor, and are operated electro-pneumatically.

arrangement of the windings in the latter machines may differ from that in the former machines.

The air-gap of a three-phase traction motor is generally larger than that of a stationary motor of similar size; and in order to obtain a high power-factor under these conditions it is necessary to (a) adopt a low frequency of supply, (b) adopt few poles, (c) employ nearly closed slots,

* For a full discussion on the leakage of induction motors see "The Alternating-current Commutator Motor," Goldschmidt (Electrician Series). Also "Calculation of the Short Circuit Current for Three-phase Motors," Oelschlager (*The Electrician*, vol. 60, p. 834).

† "Electric Motors," p. 474.

‡ Paper on "The Magnetic Dispersion in Induction Motors" (*Journal of the Institution of Electrical Engineers*, vol. 33, p. 239).

(d) design the end connections for a low leakage reactance. With some large Continental motors for locomotives, the air-gap is of the order of 2 mm. (0.08 in.), which is about 60 per cent. larger than the air-gap adopted for a stationary three-phase motor of similar output. However, the air-gap of 0.08 in. is very small in comparison with the air-gap of continuous-current railway motors (which is of the order of 0.18 to 0.25 in.). The bearings of three-phase motors must, therefore, be designed more liberally than those of continuous-current traction motors, and an efficient system of lubrication must be adopted.

The natural ventilation of polyphase traction motors is generally

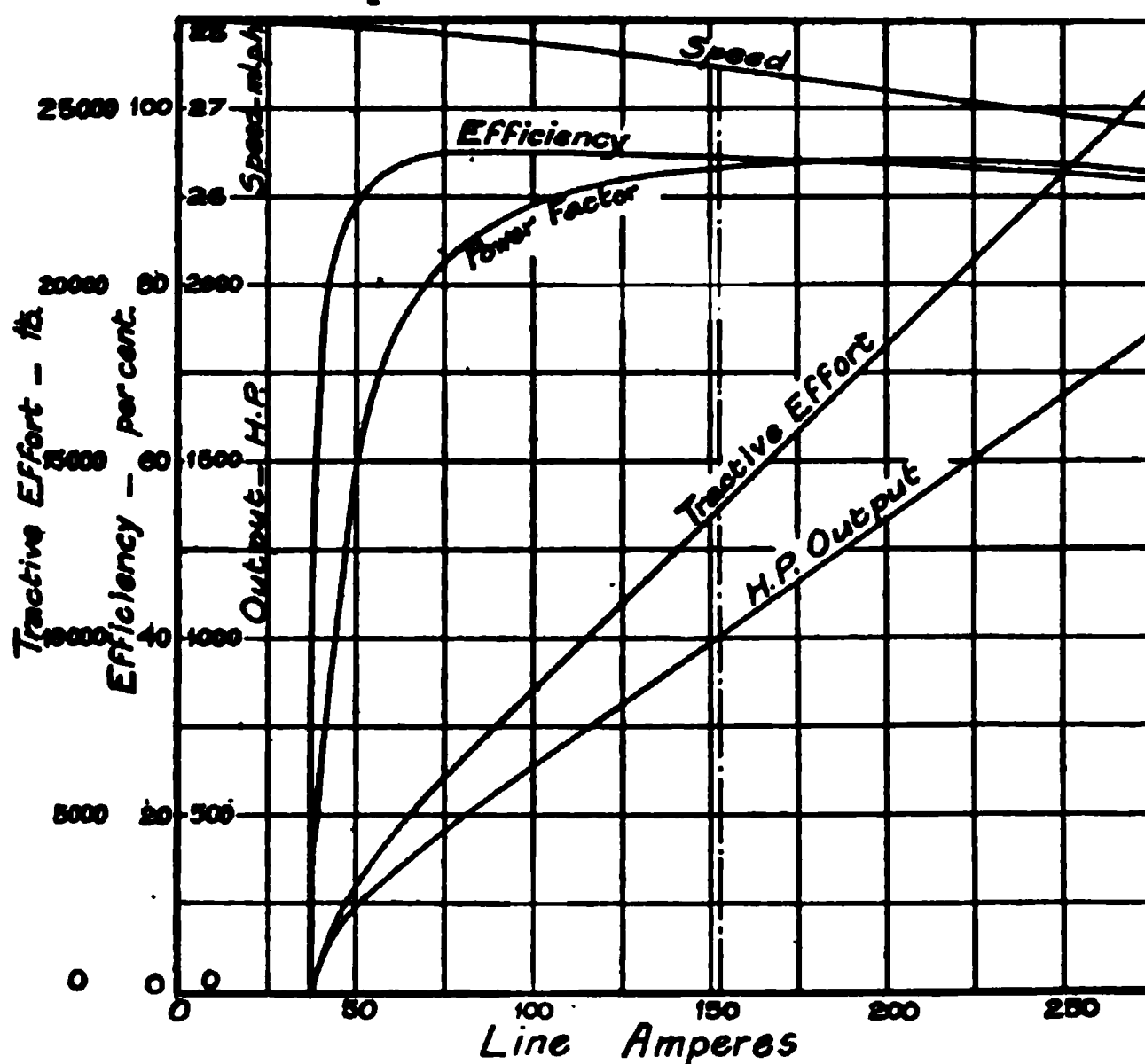


FIG. 89.—Characteristic Curves of 1000 H.P., 8-Pole, 15-Cycle, 3300-volt, Three-phase Railway Motor (wheels, 1070 mm.—42.1 in.—diameter). Società Italiana Westinghouse.

better than that of continuous-current non-ventilated motors, owing to the more open construction of the rotor core and spider. Moreover, the absence of a commutator and exposed live parts, enables the end shields to be of an open design, so that free circulation of air can occur through the motor (see Fig. 90, p. 117).

The largest portion of the total losses usually occurs in the stator, and comprises the stator core loss and the I^2R loss in the stator winding. The stator frame is, therefore, designed to secure a large radiating surface, and is either of a box section with ventilating apertures, or of a thin, solid section with radiating fins (see Fig. 90, p. 117). The losses in the stator can therefore be readily dissipated, and with an open design for the end shields the motor will attain its final temperature after a comparatively short run (of two to three hours) as indicated by the

curves of Fig. 85 which refer to a 220-H.P., 12/6 poles, 25-cycle geared motor manufactured by Brown, Boveri & Co. Hence, with motors of this design the one-hour and continuous ratings will not differ to the same extent as with non-ventilated totally enclosed motors.

Rating.—In some cases three-phase motors are rated on a one-hour basis, and in other cases on a continuous basis. The method of rating must obviously depend on the class of service on which the motor is to operate, and where this service involves long-distance runs and regenerative braking the motors must be rated on a continuous basis.

FIG. 90.—Brown, Boveri 550/850-H.P., Four-speed, 16/8-12/6-Pole, 16-Cycle, Three-phase Railway Motor.

When rated on a one-hour basis the temperature rise is usually 75°C .—as in other traction motors similarly rated—but for continuous operation the temperature rise should be limited to about 60°C ., unless special insulating materials are adopted.

EXAMPLES OF THREE-PHASE TRACTION MOTORS

Three-phase traction motors may be of the geared type—similar to continuous-current motors—or of the gearless type, in which case the transmission from the motors to the driving wheels is usually by means of side rods.

Geared motors have been adopted on the three-phase locomotives built by the **General Electric Co.** for the Cascade Tunnel electrification (Great Northern Railway, U.S.A.)* and on the split-phase locomotives built by the **Westinghouse Co.** for the Norfolk and Western Railway electrification.

FIG. 91.—Rotor of Brown, Boveri Four-speed, Three-phase Railway Motor.

Views of the stator and rotor of one of the motors for the **Norfolk and Western locomotives** are given in Figs. 86, 87, while a view showing the motors in position on the truck is given in Fig. 346 (p. 408). The motors are wound for four and eight poles, and are rated at 410 H.P.

* For a description of these locomotives see *Transactions of the American Institute of Electrical Engineers*, vol. 28, p. 1281.

for 1 hour and 325 H.P. continuously, with forced ventilation. The construction of the stator core should be noted; the punchings are riveted to steel end-rings, which are furnished with eye bolts, and are seated in a half-frame forming part of the truck. The upper portion of the motor is enclosed in a pressed steel frame which communicates with the ventilating duct on the locomotive. (See Chapter XVII, p. 403.)

The "gearless" type of motor has been developed to a considerable extent on the Continent, in connection with the electrification of the Italian State Railways and the Simplon Tunnel. The methods of mounting the motors on the locomotives are discussed in Chapter XVII.

Per cent.

Per cent.

FIG. 92.—Characteristic Curves of Brown, Boveri Four-speed, Three-phase Railway Motor (3000 volts, 16-Cycles; wheels, 1250 mm.—49.2 in.—diameter). NOTE.—Full lines denote efficiency, chain-dotted lines denote power-factor.

In general, the motors may be divided into three classes, viz.: (1) single motors with wound rotors, (2) double motors with wound rotors, and (3) single motors with squirrel-cage rotors.

The motors are arranged for either cascade, pole-changing, or a combination of cascade and pole-changing control as discussed in Chapter XI.

A typical motor—built by the **Società Italiana Westinghouse** for the passenger locomotives described in Chapter XVII (see Fig. 339, p. 403)—is illustrated in Fig. 88. This motor is designed for combined pole-changing and cascade control, the poles being changed in the ratio of 1-33:1 (i.e. 8:6). The switches for performing the functions of pole-changing, re-grouping the stator windings (for cascade working), and interconnecting the motors (for cascade working), are located on the motor frame and are operated electro-pneumatically. The two sets of slip-rings can be seen in the illustration. Two motors are located on

the framing of the locomotive, and the cranks on their rotor shafts are connected together by a "scotch yoke" through which the power is transmitted directly to the driving wheels (see Chapter XVII for details).

Typical characteristic curves for a two-speed cascade motor are given in Fig. 89, in which the high power-factor and efficiency should be noted. The motor, with forced ventilation, is rated at 1000 H.P. (one hour), 3300 volts, 15 frequency.

Four-speed changeable-pole motors with squirrel-cage rotors have been developed by Brown, Boveri & Co. for three-phase locomotives. The motors have two stator windings (wound with poles in the ratio of 1.5 : 1), and each winding is arranged so that the poles may be changed in the ratio of 2 : 1 by the method shown in Fig. 81. Therefore the four synchronous speeds are in the ratio 1 : 1.5 : 2 : 3.

In order to obtain sufficient starting torque, the squirrel-cage rotor winding is designed with a high resistance, and since practically the whole of the starting losses occur in the rotor, the ventilation of this part of the motor has received special consideration. In the **Brown, Boveri** motors the frame-heads are of open construction, as illustrated in Fig. 90, and the end-connections of the rotor winding are designed to act as fans and circulate air through the motor.

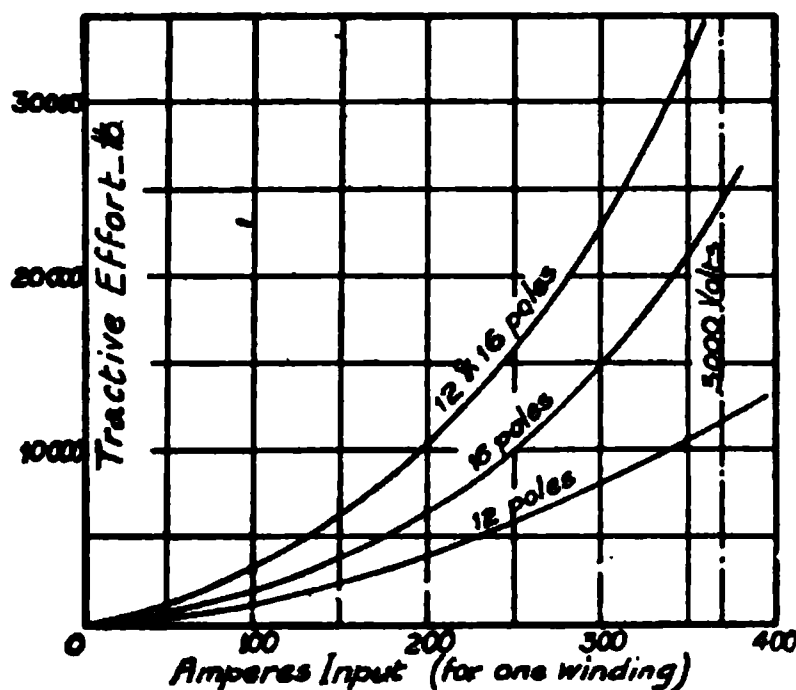


FIG. 93.—Starting Performance of Brown, Boveri Four-speed, Three-phase Railway Motor.

conductors and the shaft. Thus a large radiating surface is obtained, and, at the same time, the end connections act as fans and produce an efficient circulation of air through the interior of the motor. This type of construction is very robust, and the results obtained on the locomotives operating through the Simplon Tunnel have been very satisfactory.

In the motors constructed for the Simplon Tunnel locomotives the stator windings consist of former-wound coils located in open slots which are closed by hard wood wedges. The ends of the windings are completely enclosed in winding shields in order to protect the winding from the moist air of the tunnel. The windings are designed for the full line voltage (3000 volts), but at starting and for speed regulation they are supplied at reduced voltage from two V-connected auto-transformers.

The two motors on each locomotive are mounted "back-to-back" on the locomotive framing, and drive the wheels through a special arrangement of coupling rods, as shown in Fig. 341 (p. 404). The weight of each motor is approximately $12\frac{1}{2}$ tons.

The one-hour ratings of each motor, when supplied at 3000 volts and 16 frequency, are as follows :

Number of Poles.	Synchronous Speed. r.p.m.	H.P.
6	320	850
8	240	750
12	160	650
16	120	550

The efficiency, power-factor, and speed curves corresponding to the different numbers of poles, are given in Fig. 92, while curves of the starting torque are given in Fig. 93. These curves show the advantage of the larger number of poles at starting, and also the effect of connecting the two stator windings in parallel.

CHAPTER VII

THE TESTING OF TRACTION MOTORS

(NOTE.—It is suggested that the Standardisation Rules in Appendix II be carefully studied before this Chapter is read.)

Introduction.—Tests on traction motors may be divided into two classes, viz. (1) factory tests, which include (a) commercial tests run on standard machines, (b) special tests applied to machines of a new design; and (2) tests in service, which are generally of a special nature, and are run to ascertain if a motor equipment fulfils the guaranteed conditions of service.

It will be convenient to discuss first the factory tests applied to continuous- and alternating-current motors, and to follow this with a discussion of representative tests in service.

PART I

FACTORY TESTS ON CONTINUOUS-CURRENT TRACTION MOTORS

The A.I.E.E. Standardisation Rules (see Appendix II) define the rating of a traction motor to be “the mechanical output at the axle which causes a rise of temperature above the surrounding air not exceeding 75° C. (by thermometer) for all accessible parts except the commutator (where a rise of 90° C. is allowed), after one hour's continuous run, at the rated voltage, on a stand with the motor covers arranged to secure maximum ventilation.” This test must be run on all motors unless there is sufficient evidence to show that a machine fulfils satisfactorily the specified conditions as to temperature rise and overload capacity.

A **commercial test on a traction motor** will, therefore, include the following:

- (1) A heat-run of one hour's duration at the rated load.
- (2) A speed test at full load, in each direction of rotation, to check the position of the brushes and to ascertain if the speed of the motor is within the permissible limits. (The speeds in each direction of rotation must not differ by more than 5 per cent., and must be within 2½ per cent. of the rated speed.)
- (3) A commutation test at 100 per cent. overload; and
- (4) An insulation test, consisting of a brief application of high voltage.

With standard machines it is customary to test two machines together, in the manner indicated below, operating one machine as a motor during the first half of the heat-run, and the other machine as a motor during the second half of the heat-run. The resistances of the armature and field windings of each machine are obtained at the start and finish of the run, in addition to the temperatures by thermometer.

The insulation test is applied after the heat-run, with the machines hot, and usually consists of the application of 2500 volts (alternating) between conductors and frame for a period of one minute.

The **special tests** under heading (b), above, include (a) an efficiency and speed test over the whole of the operating range of the motor, from which the standard characteristic curves of the machine are obtained; (β) a number of heat-runs at various loads for the purpose of determining the thermal characteristics; (γ) a core-loss and saturation test.

FIG. 94.—Testing Stand for Tramway Motors.

Load tests are generally run on a **testing stand**, of which a typical example, showing the motors in position, is illustrated in Fig. 94. The stand is arranged to accommodate two similar motors, each machine being geared to a horizontal shaft carried in bearings. One machine is operated as a motor, and is loaded by operating the other machine as a generator. The latter is generally separately excited—the field winding being connected in series with the motor—and may either be loaded on rheostats or loaded back on the supply. In the latter case a booster will be required to make up the difference between the supply voltage and that of the generator armature, while in both cases a booster will usually be required for maintaining a constant voltage at the terminals of the motor.

Elementary diagrams showing the **connections** of the machines and boosters for both of these methods are given in Fig. 95. In the **loading-back method** it is necessary to start the set with the generator loaded on a rheostat load in order to prevent the machines reaching an excessive speed, the rheostat load being cut out as soon as the generator is paralleled with the supply. The load is then regulated by adjusting the field of the "load" booster, while normal voltage is maintained across the motor by regulating the field of the "line" booster.

A diagram of the **complete connections of a switchboard** for carrying out these tests on a commercial scale is given in Fig. 96. With

this switchboard it is possible (1) to take load tests by either of the above methods; (2) to operate either machine as motor in any desired direction of rotation; (3) to electrically lock the machines against each other, so that the resistances of both machines may be determined without changing the main connections; and (4) to provide for any of the special tests detailed below. It will perhaps be of interest to show how some of these combinations can be obtained. Thus, suppose

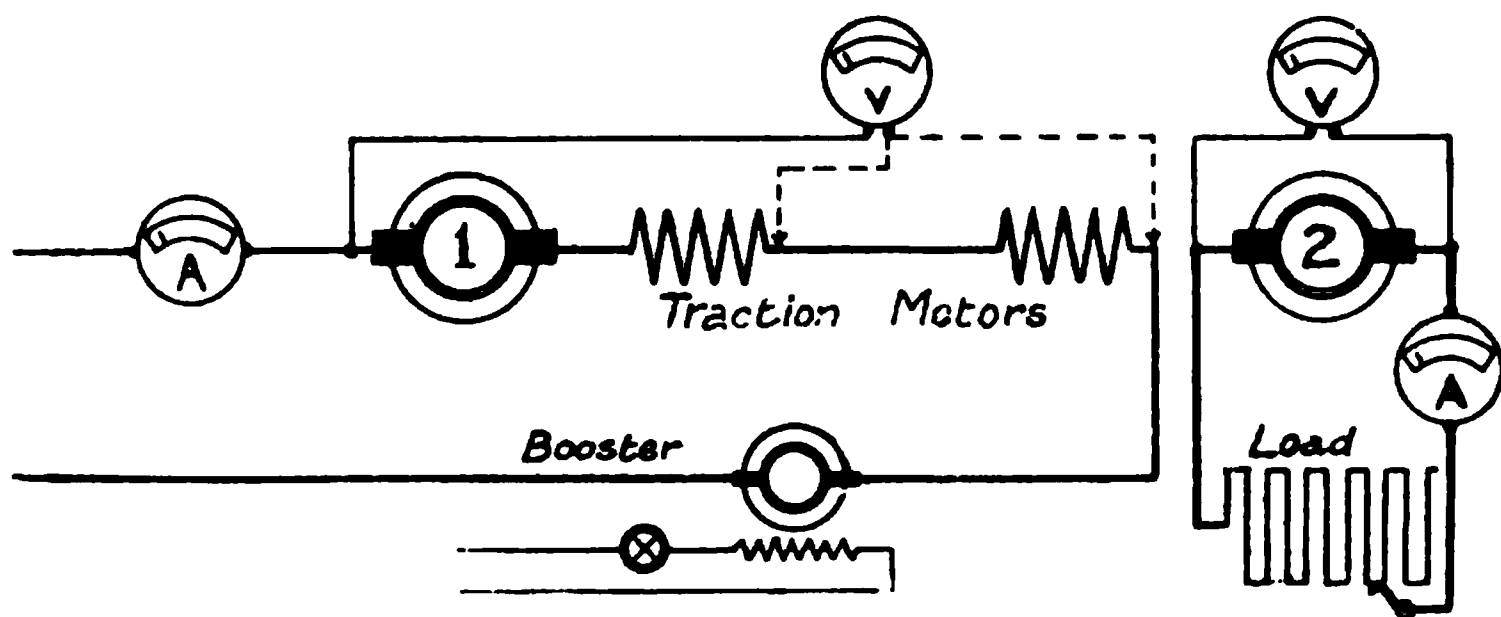


FIG. 95a.—Connections for Load Tests on Traction Motors (Rheostat Load).

No. 1 machine is to be tested as a motor by the loading-back method. Switch *A* is thrown up, and switch *B* is thrown down, the reversing switch *F* being in the position for the desired direction of rotation. The set is started up on a rheostat load, and the voltage of the generator circuit adjusted (by means of the "load" booster) to equal the line voltage, when the paralleling switch *E* is closed and the rheostat load opened

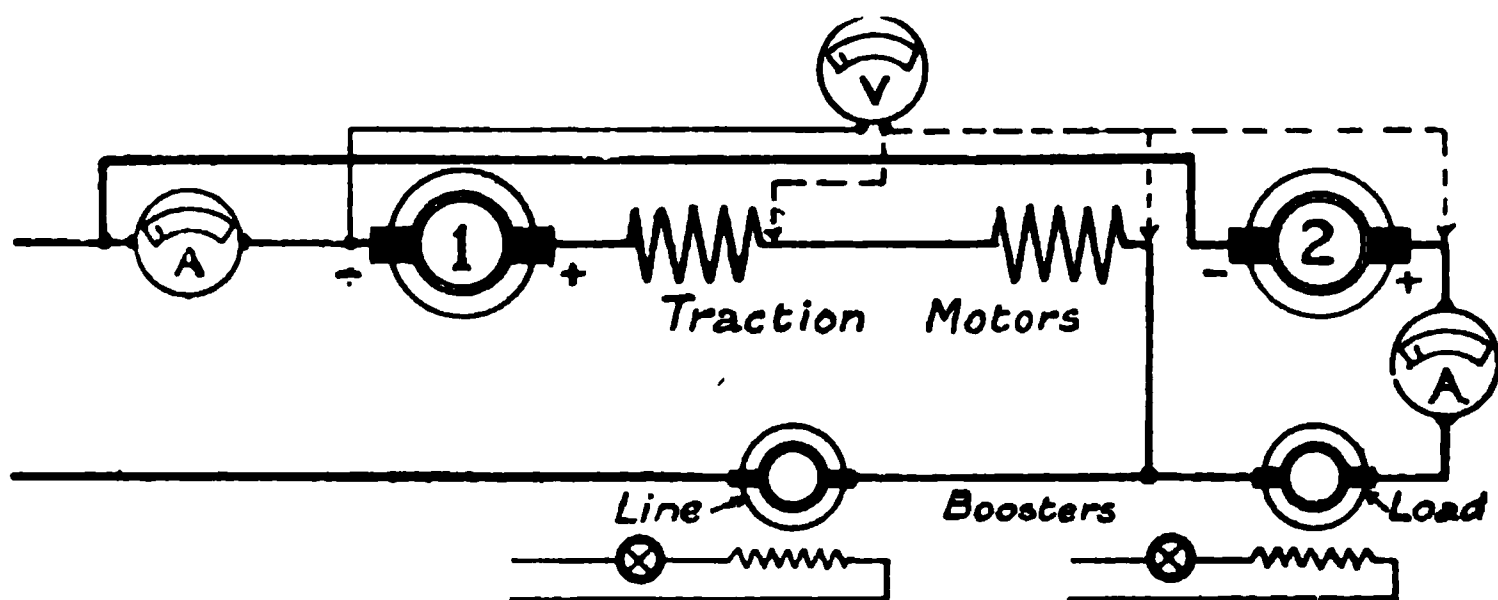


FIG. 95b.—Connections for Load Tests on Traction Motors (Loading-back Method).

on switch *H*. The voltages across the paralleling switch are read on the voltmeter *V* by transferring the voltmeter plug to receptacles *L*, *M*. After the generator has been paralleled, the voltage across the motor is adjusted to the normal value by means of the "line" booster.

If it is desired to determine the resistances of each machine, then switches *A* and *B* are kept in the above positions and switch *E* is closed, switches *C*, *H* being open, and the starting rheostat short-circuited. If the connections are traced through, it will be found that the armatures and fields of both machines are all in series across the "load" booster, which will therefore supply the current for taking the resistance tests.

It should, of course, be observed that the torque of one machine can be balanced against that of the other by throwing the reversing switches in the proper position, and under these conditions the machines will be locked against movement.

In running an **efficiency test** on the machines it is necessary to determine (a) the motor input, (b) the generator output, and (c) the

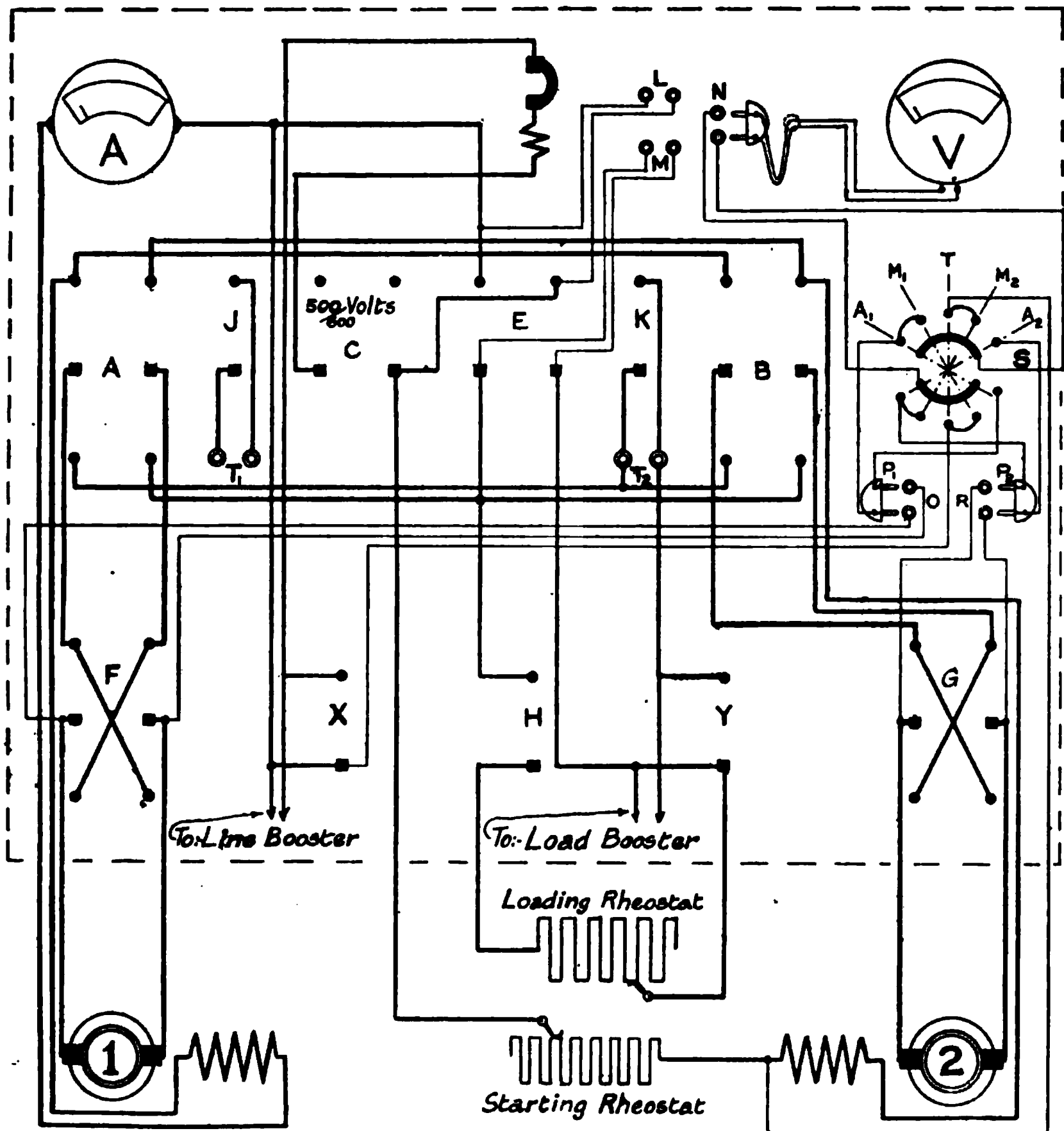


FIG. 96.—Connections of Switchboard for Testing Traction Motors.

loss in the generator field. The input and output currents are read on ammeters connected to the ammeter short-circuiting switches *J*, *K*, while the various voltages are read on the voltmeter *V*, by means of the multi-contact voltmeter switch *S*, the voltmeter plug being in receptacle *N*. In large motors the potential leads for the voltmeter should be taken off the terminals of the machines, and to provide against the reversal of the voltmeter, when the direction of rotation is changed, the potential leads from the armatures are connected to the receptacles

O , R , and connection to the voltmeter switch contacts is made by means of plugs P_1 , P_2 .

The **efficiency** of the machine operating as a motor is determined in the following manner :

Let V_1 = voltage across motor terminals,

V = voltage across motor and generator field (called the "total" voltage),

V_2 = voltage across generator armature,

I_1 = motor current in amperes (input),

I_2 = generator current in amperes (output).

Then the total losses will be—

$$VI_1 - V_2I_2.$$

Now, since the generator field is connected in series with the motor and each machine is running at the same speed, the field, core, friction, and gear losses may be assumed as equal in each machine, while the armature I^2R losses will be the only components of the total losses which differ in the two machines. Letting R_1 , R_2 equal the resistances of the motor and generator armature * respectively, we have the total loss in the motor

$$= \frac{1}{2} \{ VI_1 - V_2I_2 - (I_1^2R_1 + I_2^2R_2) \} + I_1^2R_1,$$

and, since the motor input is V_1I_1 , the efficiency will be given by

$$\eta = \frac{VI_1 - \frac{1}{2} \{ VI_1 - V_2I_2 + (I_1^2R_1 - I_2^2R_2) \}}{V_1I_1},$$

$$\text{or } \eta = 1 - \frac{0.5}{V_1} \left\{ (V + I_1R_1) - \frac{I_2}{I_1}(V_2 + I_2R_2) \right\} \dots \dots \dots (27)$$

a form which is convenient for calculation.

If the motor voltage V_1 is maintained constant at 500 volts, the percentage efficiency will be given by

$$\eta\% = 100 - 0.1 \left\{ (V + I_1R_1) - \frac{I_2}{I_1}(V_2 + I_2R_2) \right\}, \dots \dots \dots (27a)$$

and at 600 volts by

$$\eta\% = 100 - 0.083 \left\{ (V + I_1R_1) - \frac{I_2}{I_1}(V_2 + I_2R_2) \right\} \dots \dots \dots (27b)$$

When a large number of results have to be worked up, the working is conveniently done in tabular form, as shown in the example in Table VIII.

In cases where the rheostat method of loading is adopted,† a greater degree of accuracy can be obtained by measuring directly the *differences* between the motor and generator currents and voltages, instead of determining each of these quantities separately. The connections ‡ for this method are shown in Fig. 97, r_1 , r_2 being standard resistances or shunts and MV a millivoltmeter, which is of such a range that a large

* For accurate calculations these should include the brush contact resistance, otherwise the brush I^2R loss will be included in the "constant" losses.

† This method is due to Professor E. Wilson. See a paper read before Section G of the British Association, 1903. *Electrician*, vol. 51, p. 891.

‡ These connections cannot be adopted for the loading-back method of testing.

deflection can be obtained for the maximum value of $(I_1 - I_2)$. If $(I_1 - I_2) = i$, and $(V_1 - V_2) = v$, then the above equation (27) for efficiency becomes

$$\eta = 1 - \frac{0.5}{V_1} \left[(V + I_1 R_1) - \frac{I_1 - i}{I_1} \{ (V_1 - v) + R_2 (I_1 - i) \} \right] \quad \dots \quad (27c)$$

TABLE VIII

METHOD OF TABULATION FOR WORKING OUT EFFICIENCY TEST

Rating of Motor, 28 H.P., 500 volts, 450 r.p.m.

Average Hot Resistances for Test :—

Motor : Armature, 0.48 ohm ; brushes, 0.05 ohm ; field, 0.84 ohm
($\therefore R_1 = 0.48 + 0.05 = 0.53$ ohm).

Generator : Armature, 0.465 ohm ; brushes, 0.05 ohm ; field, 0.84 ohm ($\therefore R_2 = 0.465 + 0.05 = 0.51$ ohm).

Resistances at 75° C. :—

Armature, 0.42 ohm ; field, 0.86 ohm ; brushes, 0.05 ohm. Total, 1.33 ohm.

Motor.			Total Volts V.	Generator.			$I_1 R_1$	$V + I_1 R_1$	$I_2 R_2$	$V_2 + I_2 R_2$	$\frac{I_2(V_2 + I_2 R_2)}{I_1}$	$\frac{V + I_1 R_1 - \frac{I_2(V_2 + I_2 R_2)}{I_1}}{I_1}$	$\frac{100 - 0.1 \{ (V + I_1 R_1) - \frac{I_2(V_2 + I_2 R_2)}{I_1} \}}{I_1}$
Volts V_1	Am- peres I_1	Speed.		Arma- ture Volts V_2	Arma- ture Amperes I_2	Field Am- peres.							
500	78	385	573	352	66	78	41.4	614.4	33.7	385.7	327	287	71.3
"	70	405	567	369	59.5	70	37	604	30.3	399.3	340	264	78.6
"	60	442	557	383	50.2	60	31.8	589	25.6	408.6	342	247	75.3
"	50	482	542	408	39.8	50	26.5	568.5	20.3	428.3	341	227	77.3
"	40	522	538	427	31.6	40	21.2	559	16.1	443	350	209	79.1
"	30	600	528	443	22.3	30	15.9	544	11.3	454.3	338	206	79.4
"	20	728	518	463	12.6	20	10.6	528	6.4	469.4	296	232	76.8
"	12	1085	512	480	5.1	12	6.4	518	2.6	482.6	204	314	68.6

In working out standard characteristic curves, such as those given in Figs. 30, 31, 32, the test readings are corrected for a copper temperature of 75° C., and for a gear and friction loss, at the rated load, equivalent to 5 per cent. of the input (see Appendix II). Thus the actual gear loss, which would otherwise be a variable quantity in different machines of the same rating, is replaced by a definite quantity which is constant in machines of equal rating, and in this manner all characteristic curves are directly comparable.

The corrections may be conveniently applied to the uncorrected efficiency curve in the following manner. Since the efficiency curve is plotted with current input as abscissæ, and the voltage is constant, the ordinate between any point of the curve and 100 will represent the losses as a percentage of the input. Hence the I^2R losses will be represented by a straight line drawn through the point 100, 0, as indicated in Fig. 98. The intercept between this line and the efficiency curve will therefore represent the core, friction, and gear losses as a percentage of the input. When the core loss is known, the actual gear and friction loss can be deduced and corrected to the values given in § 1100, Appendix

II. The efficiency curve in Fig. 98, which refers to the test results in Table VIII, has been corrected in this manner, the corrected curve being shown in full line and the uncorrected curve in dotted line.

The **speed curve is also corrected**, to correspond to a copper temperature of 75°C. , in the following manner :

Let R denote the resistance of the armature and field windings at a temperature of 75°C. , R_1 the resistances during the test, n_1 the test speed, and n the corrected speed, both corresponding to a current I . If the terminal voltage during the test has been held at its normal value V_1 , then

$$\frac{n_1}{n} = \frac{V_1 - IR_1}{V_1 - IR},$$

whence

$$n = n_1 \left(\frac{V_1 - IR}{V_1 - IR_1} \right). \quad (28)$$

If the speed n_1 has been determined at a voltage (V'_1) other than normal, then

$$n = n_1 \left(\frac{V_1 - IR}{V'_1 - IR_1} \right).$$

The **speed curve is usually plotted in miles per hour**, corresponding to the diameter of wheel and gear ratio to be used. If D represents the diameter of driving wheels in inches, and γ represents the gear ratio, then the speed S of the car (in ml.p.h.), corresponding to a motor speed n (r.p.m.), will be

$$S = \frac{nD}{\gamma} \times \frac{60\pi}{12 \times 5280} = 0.00297 \frac{nD}{\gamma} \quad (29)$$

The **torque curve** can readily be obtained from the efficiency and speed curves. It is generally plotted in terms of the tractive-effort (expressed in lb.) at the driving wheels. Thus, for a current of I_1 and (normal) voltage V_1 , the tractive-effort (F) in lb. will be

$$F = \frac{V_1 I_1 \eta}{SD} \times \frac{33000 \times 60 \times 24}{2\pi \times 746 \times 100 \times 5280} = \frac{0.0192 V_1 I_1 \eta}{SD} \quad (30)$$

η and S denoting the percentage efficiency and speed (ml.p.h.) respectively, which are obtained from the curves, and D the diameter of the driving wheels in inches.

The **core loss** (i.e. the iron loss in the armature core and the eddy-current losses (if any) in the armature conductors, armature flanges, &c.) may be determined by two methods, viz. (1) by driving the traction motor by a smaller shunt motor and measuring the input to the latter when the former is (a) unexcited, (b) excited with various field currents, the speed being held constant throughout ; or (2) by running the traction motor light, with separately excited field, and measuring the input to the armature at various excitations, the speed for each excitation being obtained from the speed-curve of the motor. Although both of these methods are in use, method (1), notwithstanding its being a more lengthy process than method (2), is to be preferred where accurate results are required, since, by the proper choice of the driving motor, a large variation of the current input can be obtained between zero and maximum excitation on the traction motor.

When the core loss is derived by running the traction motor light, as

in method (2), the variation in the current input is small, and, in consequence, the accuracy is not very great. This method, however, has the advantage of being performed quickly, and can be adopted where only a rough indication of the core loss is required.

Considering method (1) in detail, the procedure is practically the same as that adopted for a core-loss test on a continuous-current generator or stationary motor. The armature shaft of the traction motor is belted to a small shunt motor of such a size that the maximum current input (corresponding to the maximum excitation on the traction motor) does not exceed 60 per cent. of the full load current.* The field winding of this motor is separately excited, and the armature is run from a circuit of which the voltage is under control. The field winding of the traction

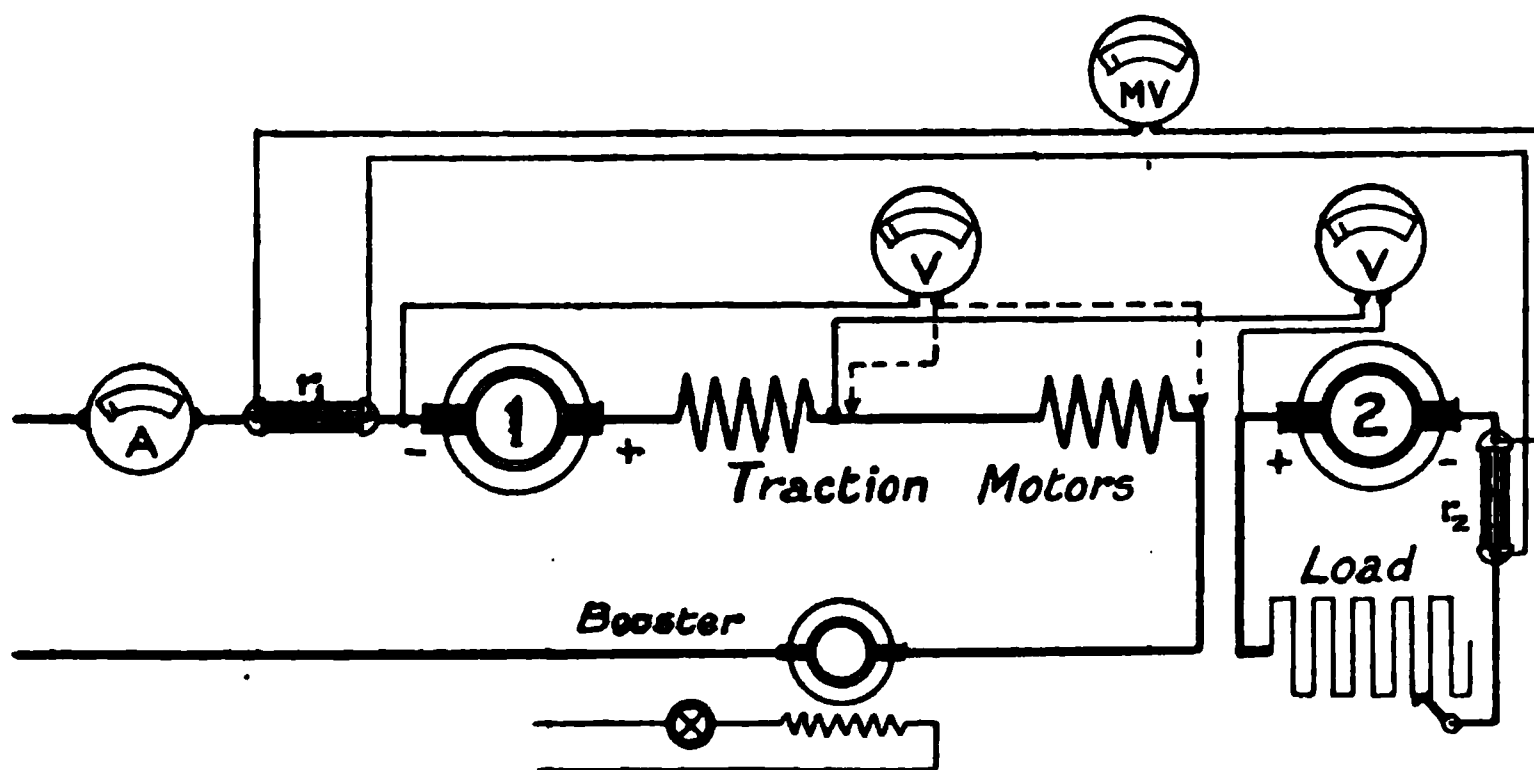


FIG. 97.—Connections for Efficiency Tests on Traction Motors.

motor is separately excited from a low voltage supply. Instruments are connected in the armature and field circuits of both machines, as indicated in Fig. 99. A series of readings are taken at various exciting currents on the traction motor (from zero to the maximum), the field current of the driving motor being maintained at a constant value, and the speed being held constant throughout by adjusting the voltage supplied to the armature. Under these conditions the core loss for a given exciting current will be given by the increase in the input to the driving motor (corrected for I^2R loss) between zero excitation and the given value. A typical set of readings and the values of the core loss deduced therefrom are given in Table IX. Similar sets of observations will be required at other speeds in order to obtain the "**characteristic core-loss curve**" (which shows the core loss at any load when the motor is supplied at constant voltage).

The **results** are plotted with exciting current as abscissæ, and the speed-curve of the motor is plotted on the same sheet, as shown in Fig. 100. To obtain the characteristic core-loss curve, we must ascertain

* Generally, the rating of the driving motor should be about 10 to 15 per cent. of that of the machine under test. To obtain good results the following conditions should be fulfilled:—

(1) Maximum current input to driving motor should not exceed 60 per cent. of the full load current; (2) Input current when driving the machine under test unexcited should not exceed 20 to 25 per cent. of the full load current.

the currents (from the speed-curve) corresponding to the speeds of the individual core-loss tests. In this manner a single point is obtained on each core-loss curve, and the curve through these points will be the characteristic core-loss curve.

If speed-curves corresponding to voltages other than normal are also plotted, the characteristic core-loss curves for these voltages can readily be obtained.

TABLE IX

TYPICAL SET OF READINGS FOR CORE-LOSS TEST

Resistance of Armature Circuit of Driving Motor = 1.12 ohms.

Machine under Test.			Driving Motor.			Input to Driving Motor (Watts).	I ² R Loss in Armature Circuit of Driving Motor (Watts).	Input less I ² R Loss (Watts).	Core Loss (Watts).
Speed.	Field Amperes.	Armature Volts.	Armature Volts.	Armature Amperes.	Field Amperes.				
400	0	..	188	3.02	0.6	568	11	557	..
"	20	367	192	5.03	"	966	28	938	381
"	25	401	192.5	5.67	"	1092	36	1056	499
"	30	423	193	6.3	"	1216	44	1172	615
"	35	443	194.5	6.82	"	1327	52	1275	718
"	40	463	195.5	7.47	"	1460	63	1397	840
"	45	475	196.2	7.9	"	1550	70	1480	923

The **saturation curve** of the motor is obtained at the same time as the core-loss test by observing the armature voltage at each value of the exciting current. The flux is then calculated and plotted against the exciting current, or the ampere-turns per spool.

In the second method, the field of the traction motor is separately excited and the armature is run light from a variable voltage supply. Readings are taken of the input to the armature at various values of the exciting current and speed (the speed for a given excitation being adjusted to that corresponding to this current on the speed-curve). The input so obtained will be equal to the core and friction losses.

To separate out the core loss the machine is run light—as a series motor—on a low voltage circuit, and the input to the armature is observed for speeds corresponding to those in the previous test. Since the excitation will be very low, the input to the armature may be taken as equivalent to the friction loss. Provided that the speeds have been correctly adjusted, the difference between the two tests will give the characteristic core-loss curve without further calculations.

A modification of the above method which is sometimes adopted is shown in Fig. 101. In this case the armature is connected in series with the field winding, but is shunted with a variable resistance R , and the machine is run light from a 500-volt circuit. The field current is adjusted by varying the shunt resistance R , and the speed is adjusted to the precise value by the rheostat r . It will be realised that this method is extremely wasteful, and its use should be restricted to the smaller traction motors when no low-voltage supply is available.

A condition essential to all core-loss tests is that readings must only be taken after the speed has become steady. When method (1) is

adopted, it is necessary to take precautions against an alteration of the friction during the individual tests.

The **thermal characteristic** of a traction motor is a curve showing the time that the motor will carry various loads at normal voltage with a temperature rise of 75°C. , the machine being at atmospheric temperature at the start, and the conditions of ventilation being the same as those for the standard one-hour test. Hence, to obtain this characteristic, it is necessary to take heat-runs at different loads and normal voltage. In these runs the temperatures of the field coils which are accessible are recorded every 15 minutes, and in this manner an indication of the length of the run is obtained. The run should, of course, be stopped when the temperature rise reaches 75°C. , and the complete temperatures of all parts obtained.

In many cases, however, the

thermal characteristic of the armature is not identical with that of the field, and in some cases the armature heating is the limiting feature at all loads. Under the latter conditions the runs will have to be stopped

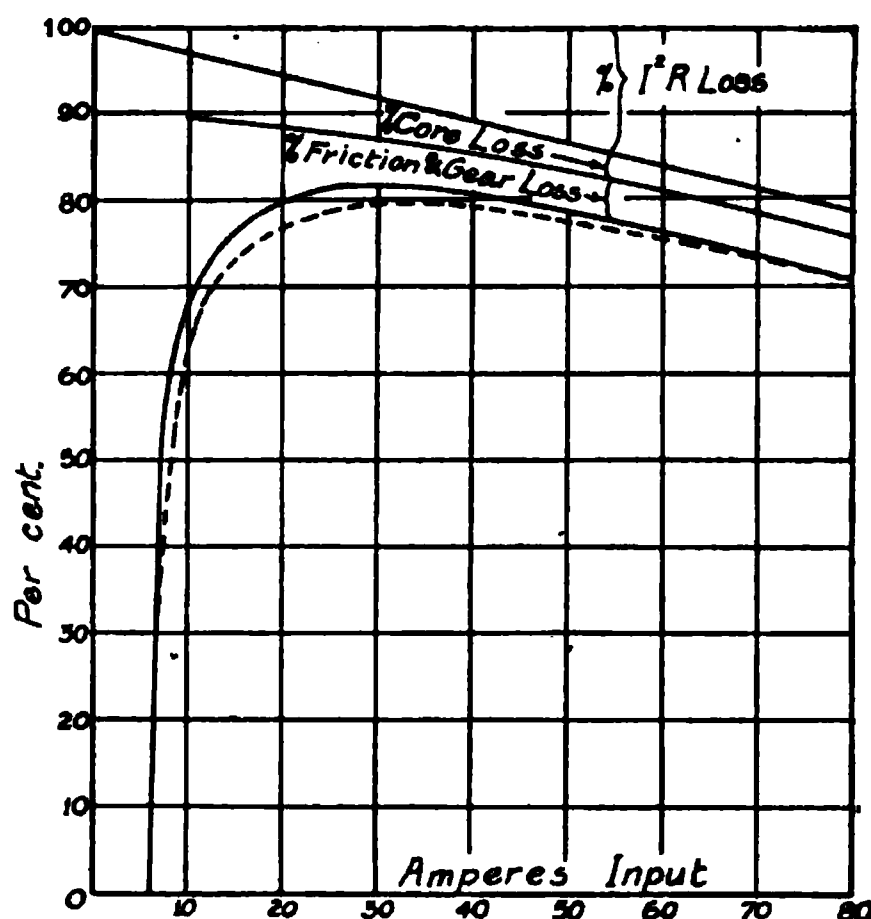


FIG. 98.—Method of Correcting Efficiency-curve to Standard Friction and Gear-loss.

before the field winding has attained the standard temperature rise (75°C.), and, if the temperature rise of the armature differs from this, the length of the run to give the standard temperature rise will have to be obtained either by extrapolation or from another heat-run at the same load.

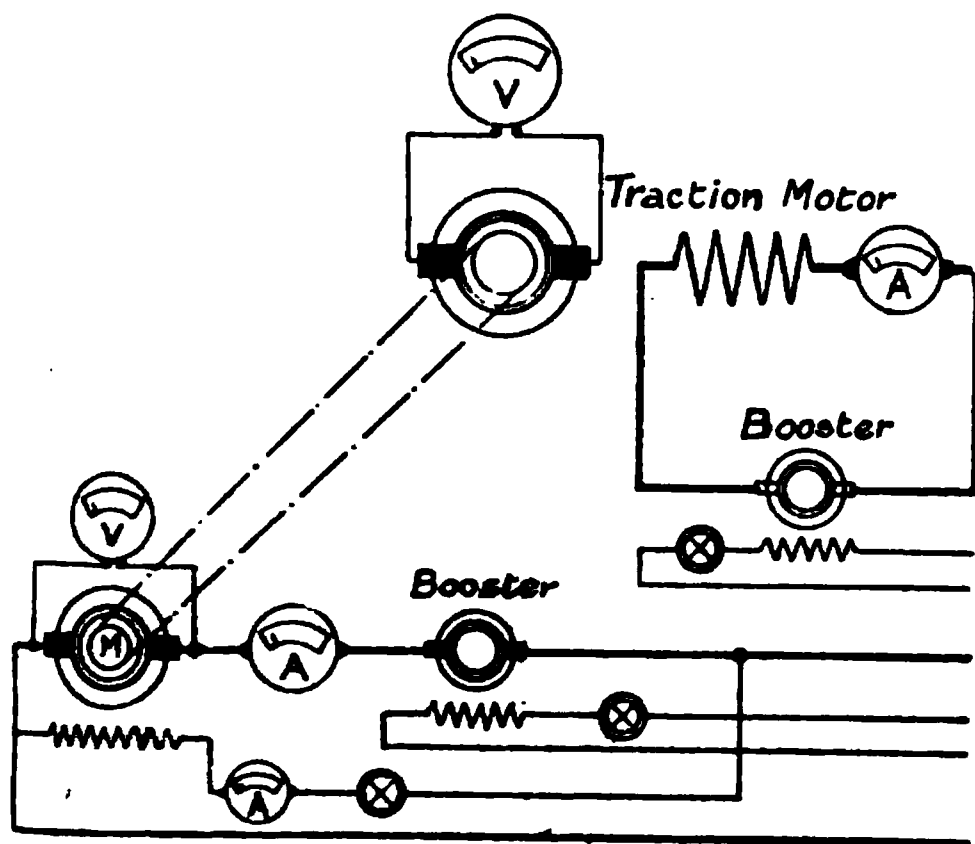


FIG. 99.—Connections for Core-loss Test on Continuous-current Traction Motor.

The results of a series of heat-runs, for the determination of the thermal characteristic of a railway motor, are shown graphically in Fig. 102, and the thermal characteristic deduced from these tests is plotted in Fig. 103.

In large motors the armature heating is generally limiting for all loads, but in small motors the field heating may be limiting at heavy loads, and the armature heating limiting at light loads. The thermal characteristic in this case will not be a smooth curve, but will con-

sist of portions of the thermal characteristics of the armature and field.

These thermal characteristics are useful in showing how the temperature of a motor will be affected by steady loads of definite duration. The **continuous rating** of the motor obtained from these tests will differ from the continuous rating of the machine when operating under service conditions, on account of the distribution of losses not being the same in each case.

When the service on which a given motor has to operate is known, the approximate temperature rise of the machine can be obtained from a heat-run in which the losses in the motor are equivalent to, and dis-

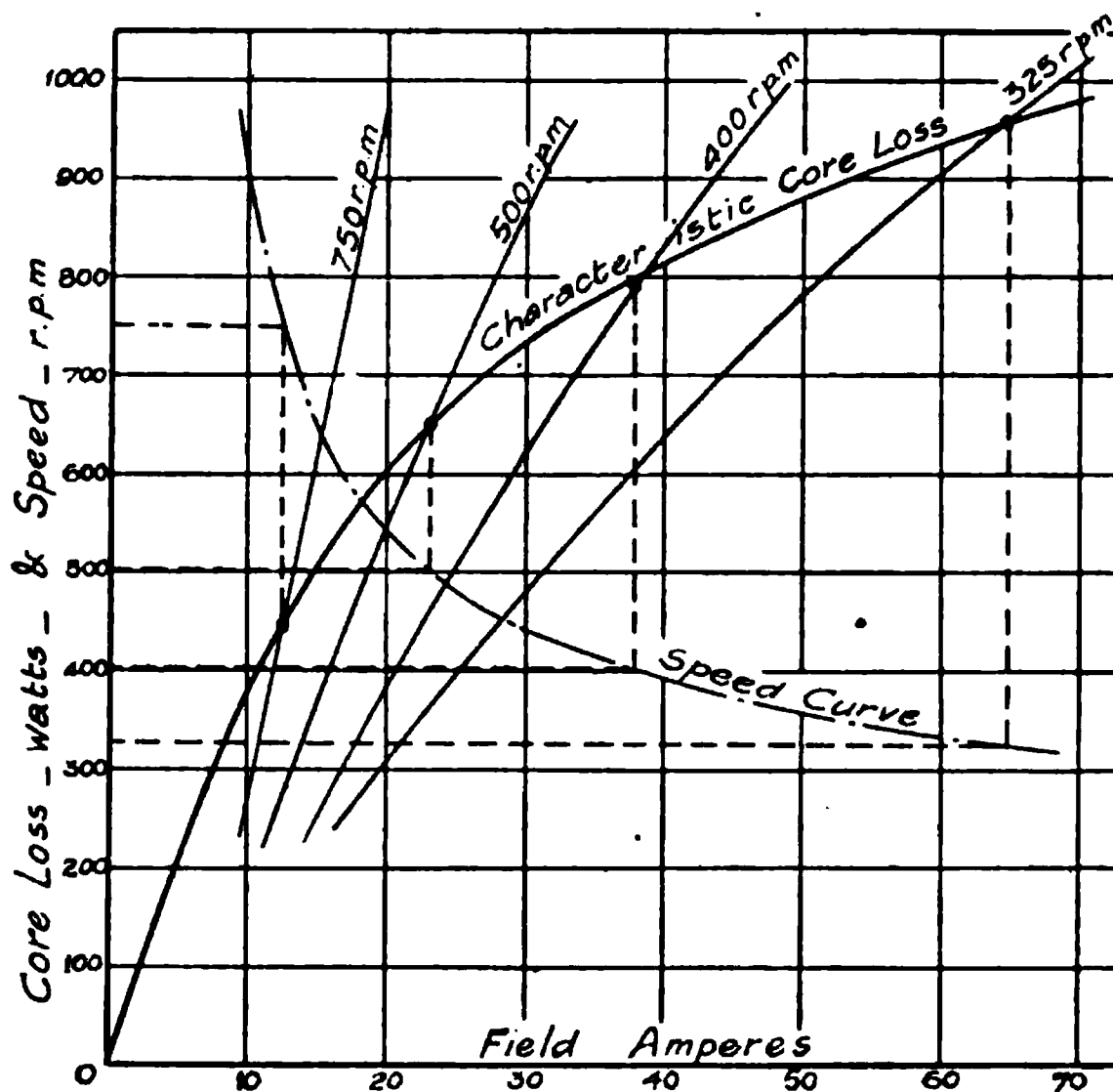


FIG. 100.—Results of Core-loss Test on Traction Motor.

tributed in the same ratio as, the average losses in service, the motor covers being arranged as in service. The heat-run is continued until a constant temperature is reached, and in this manner we obtain the continuous **service capacity** of the motor (see Standardisation Rules, §1104). The temperature rise obtained by this method, however, will be slightly higher than that obtained in service, on account of the better ventilation in the latter case.

The method of obtaining the voltage and current at which this test must be conducted is as follows. From the service speed-time curves the corresponding curves of the voltage and current for each motor are obtained. The mean voltage and R.M.S. current are then calculated over the whole period in which the motor is in service, and these values adopted for the heat-run. It is apparent that the losses in the motor during this test will have the same value as the average losses in service, and, moreover, the ratio of the distribution will be the same in each case.

When this test is run on a self-ventilated machine, the speed of the

armature during the test must be equal to that corresponding to the schedule speed in service. The voltage corresponding to this speed may differ from the mean voltage in service, and in this case the test must be run with the total armature loss and the field loss equivalent to the average values obtained above, although the ratio of the armature I^2R loss to the core loss may not be the same in the two cases.

PART II

FACTORY TESTS ON ALTERNATING-CURRENT TRACTION MOTORS

In view of the various types of alternating-current motors which have been developed for electric traction and their limited use, we can only refer to the factory tests in a general manner, and shall, in general, only consider single-phase commutator motors.

Single-phase motors, for operating suburban traffic, should be given a **commercial test** in a similar manner to continuous-current motors.

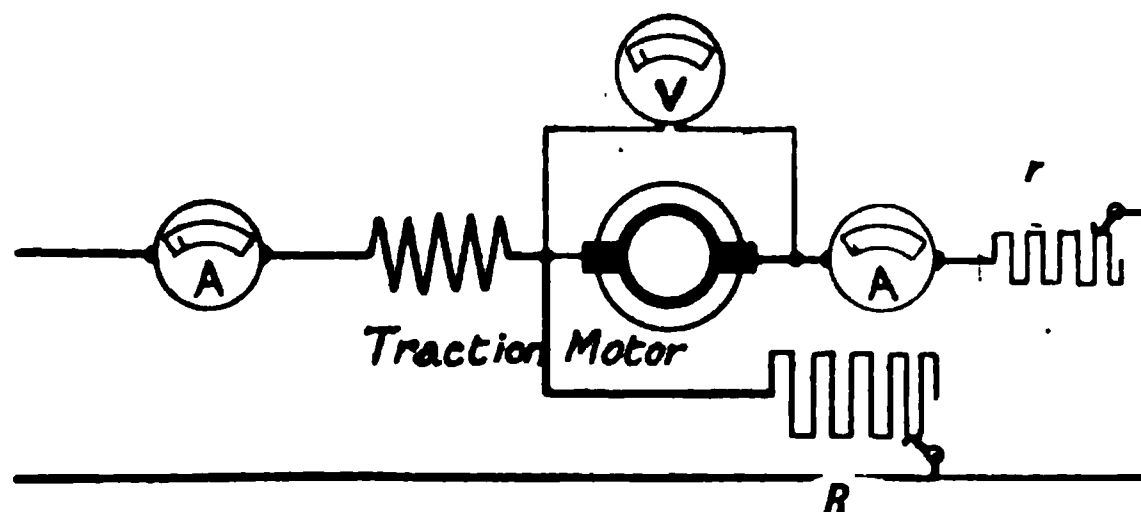


FIG. 101.—Connections for Core-loss Test by Running-light Method.

Each motor should therefore be run for one hour at its rated load with normal voltage and frequency, the resistances and temperatures being obtained in the usual manner. This test should be followed by a speed test in each direction of rotation, a commutation test at various loads, including starting, and an insulation test. In addition to these tests, the impedance of the motor should be measured at normal frequency with the armature stationary.

The loading-back method cannot be applied conveniently to single-phase motors, and in consequence the load must take the form either of a continuous-current generator or a mechanical brake.* With **compensated series motors**, however, two machines may be coupled together (or mounted on a test stand in a similar manner to continuous-current motors) and one machine operated as a separately-excited continuous-current generator. This arrangement is convenient for **heat-runs** and load tests in which efficiency readings are not required, but for efficiency tests the motor must be loaded on a brake and the output determined mechanically.

In **efficiency tests** readings are obtained of the input (by wattmeter and ammeter), torque and speed over a range of loads at constant voltage and frequency. The readings are then corrected to a definite copper temperature and gear loss (if any) in a manner similar to that

* The Froude water-dynamometer is very convenient for this purpose.

adopted for continuous-current motors, and the efficiency and power-factor calculated, while the torque and armature speed are converted into tractive-effort and train speed, to correspond to the operating conditions. The results are then plotted against input amperes (as abscissæ), thus giving the characteristic curves of the motor.

For the calculation of speed-time curves, the above characteristic curves must be supplemented by others, showing the performance of the motor when operating at the voltages corresponding to the various tappings on the main transformer; while, for the calculation of energy consumption and the load on the distributing system, the input to the primary of the main transformer will be required. In cases where each motor is fed from a separate transformer—as in some locomotives—the characteristic curves of the transformer can be readily combined with those of the motor, and a set of curves (similar to Fig. 74) obtained,

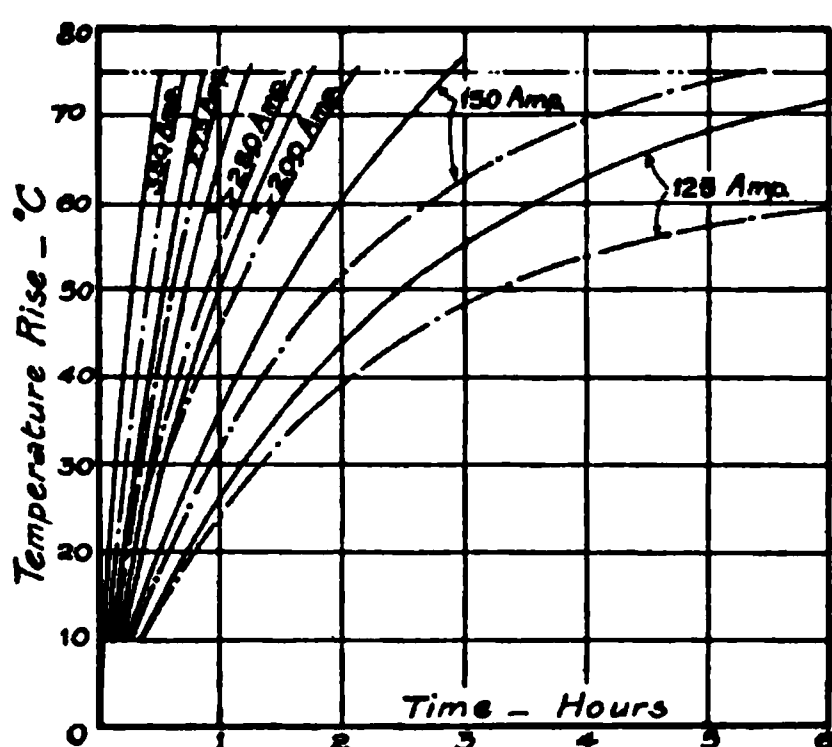


FIG. 102.—Results of Thermal Tests on Railway Motor. NOTE.—Full lines refer to armature, chain-dotted lines refer to field.

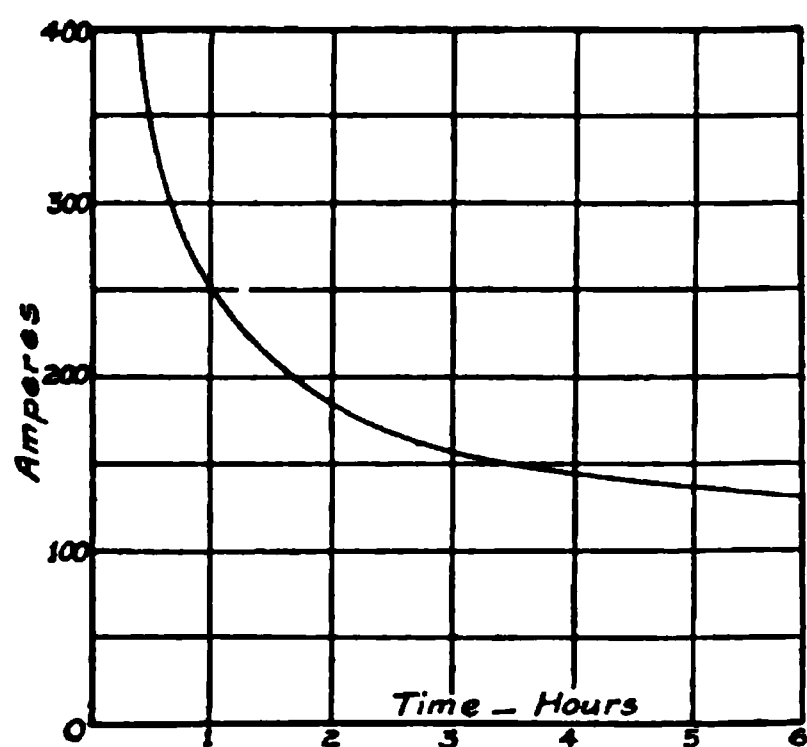


FIG. 103.—Thermal Characteristic deduced from Fig. 102.

in which are plotted (with primary current as abscissæ) the overall efficiency, the power-factor, the tractive-effort, and the speed-curves corresponding to the various ratios of the main transformer. When motors of moderate size are adopted—as in motor-coaches—it is the general practice to supply two or more motors from one transformer, and in this case the correct proportion of the transformer losses must be allocated to each motor in determining the combined efficiency curve.

The method of conducting the tests for the determination of the **thermal characteristics** will, in general, be similar to that adopted for continuous-current motors, of which full particulars have been given above.

Core loss.—In single-phase commutator motors, core losses occur in the field structure (or stator core) as well as in the armature core. The loss in the latter consists of two components, one due to the alternating flux and the other due to the rotation of the armature. The core loss in the stator (and the component of the armature core loss which is due to the alternating flux) will be supplied by the exciting current,

and can therefore be measured by a wattmeter in this circuit. The other component of the armature core loss (which is due to the rotation of the armature) can be determined by measuring the power required to drive the armature, in exactly the same manner as if we were dealing with a continuous-current machine. These tests must be conducted with the brushes raised from the commutator, as otherwise the copper losses in the field and armature windings (resulting from the circulating currents in the coils short-circuited by the brushes) will be included with the core losses.

In order to obtain the magnitude of the losses due to the circulating currents, it is the practice, in core-loss tests, to take two tests, one with all brushes on the commutator, and the other with all brushes raised from the commutator.

The method of procedure, in the case of a core-loss test on a compensated-series motor, is as follows. The main-field winding (without the compensating or commutating-pole windings) is arranged for separate excitation from a variable voltage supply of the correct frequency, and a wattmeter, an ammeter, and a voltmeter are connected in the circuit. (See Fig. 104.)

The armature is arranged to be driven at various speeds from a small shunt motor, the armature of which is connected to a variable voltage supply, while the field is separately excited at a constant current. An ammeter and a voltmeter are connected in the armature circuit of the driving motor.*

The brushes of the motor under test are removed, and a series of readings are then taken over a range of exciting currents (from zero to about 50 per cent. overload) at four or five different speeds,† the speed being maintained constant for each set of readings. In this manner both components of the rotor core loss, together with the stator core loss, are determined at the same time. Provided that there are no circulating currents in the armature due to transformer action,‡ the wattmeter in

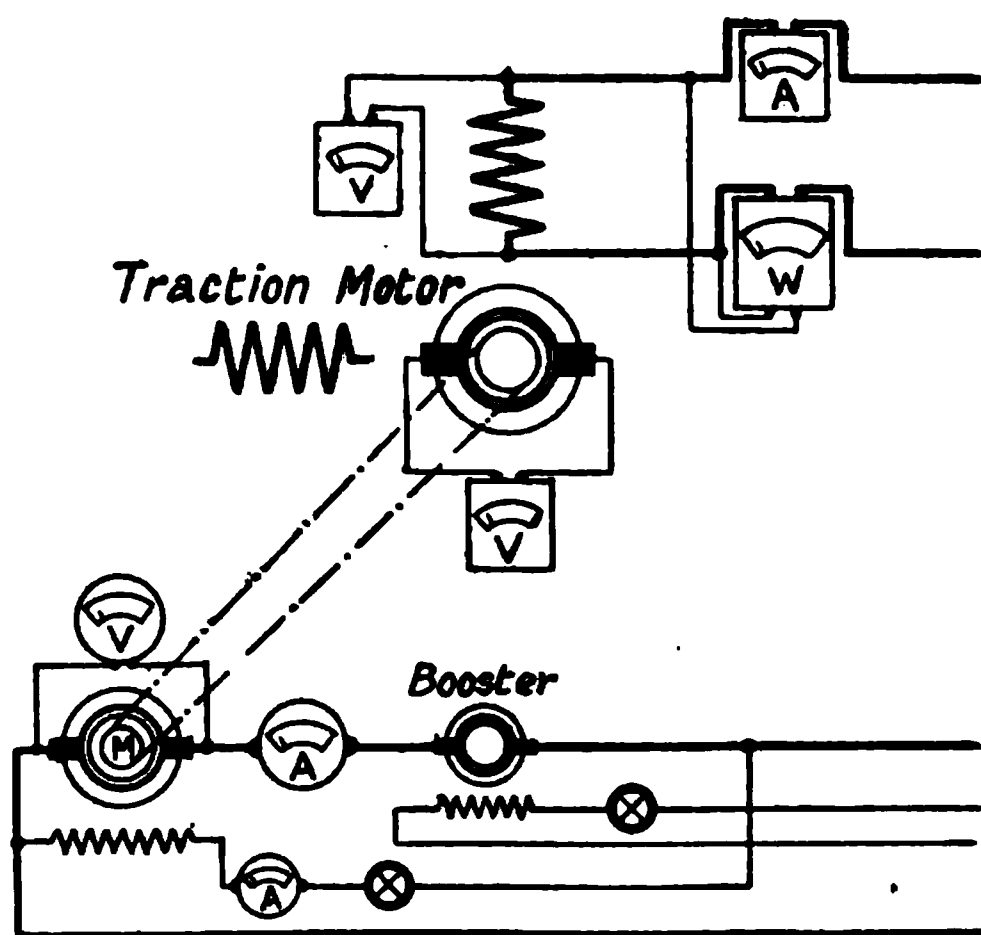


FIG. 104.—Connections for Core-loss Test on Compensated-series Motor.

* For the relation between the sizes of this motor and the machine under test, see footnote on p. 129.

† Or, for each value of the exciting current the corresponding speed is obtained from the speed-curve, and readings taken at this speed with and without excitation. In this manner the points on the characteristic core-loss curve are determined directly, but the results will be affected to a much greater extent by inaccuracies in individual readings than when the test is conducted in the manner detailed above. Moreover, the results only give the characteristic core-loss curve for one operating voltage.

‡ Circulating currents may be produced in multiple-circuit armature windings if they are unbalanced magnetically or electrically.

the field circuit will measure the core loss in the stator and armature (due to the alternating flux) + the I^2R loss in the field winding. Similarly, the input to the driving motor, when corrected for the I^2R loss in its armature, will, in the absence of circulating currents, represent the core loss (due to the rotation of the armature) + the friction and constant losses in the set. The latter are, of course, given by the corrected readings corresponding to zero excitation on the machine under test.

When the readings have been corrected in this manner and the results plotted with exciting current as abscissæ, we shall obtain one curve for the component of the core loss which is due to the alternating flux, and a set of curves—similar to those in Fig. 100—for the component of the core loss which is due to the rotation of the armature. The characteristic core-loss curve can be obtained from these curves in the manner already shown.

Fig. 105 represents the results of a core-loss test on a compensated-series motor.

In order to determine the losses (due to circulating currents) in the armature coils which are short-circuited by the brushes, the above tests are repeated with all the brushes in position. The wattmeter reading in this case will include the losses in the short-circuited coils (which are due to transformer action), and also any additional iron losses due to the reaction of the circulating currents. Hence, these losses will be represented by the difference in the wattmeter readings corresponding to the same exciting currents in the two tests (*i.e.* with brushes and without brushes). Similarly, any losses in the armature due to circulating currents (produced by the coils, short-circuited by the brushes, cutting leakage fluxes in the neutral zone, or by magnetic or electric dissymmetry) will be included in the input to the driving motor.

PART III

SERVICE TESTS

Service tests can be grouped into two classes, viz. (1) these which are conducted under *actual* service conditions, involving runs of various lengths (corresponding to the distances between the stations) at a given mean schedule speed; and (2) those which are conducted under *equivalent*, or average, service conditions, on level track, for the purpose of obtaining data on the motors.

The tests in class (1) are of the order of "official" tests, and are usually run to ascertain if a given equipment fulfils the manufacturers' guarantees; while those in class (2) are of the nature of experimental tests, the object of which is the determination of data from which the "service-capacity" curves of the motors can be obtained. These curves show the mean schedule speeds at which a motor is capable of operating various services with a given temperature rise; the nature of the service being expressed by (*a*) the number of stops per mile, (*b*) the train weight per motor.

It is apparent, therefore, that these **service-capacity curves** are of considerable value to manufacturers, and we shall now consider the manner in which the tests are conducted for their determination.

Now, since the service capacity of a motor is limited by the heating resulting from the I^2R and core losses, which occur during the periods in which power is supplied to the motor, it is obvious that the magnitude and distribution of these losses will vary with the class of the service. Thus, in suburban service, the greater portion of the I^2R losses will occur during acceleration and speed-curve running; while the core loss will have its greatest value at the end of the accelerating period, and will probably exceed the armature I^2R loss during the free-running period. On account of the large thermal capacity of the motor, the temperature of the various parts will not follow appreciably the fluctuations in the losses, and a steady temperature will be attained when the average rate of generation of heat is balanced by the rate at which the heat can be dissipated in radiation, convection, &c.

Therefore, in order to **determine the service capacity of a motor**, we must operate the motor under uniform service conditions (corresponding to a particular service) until the temperature of the machine

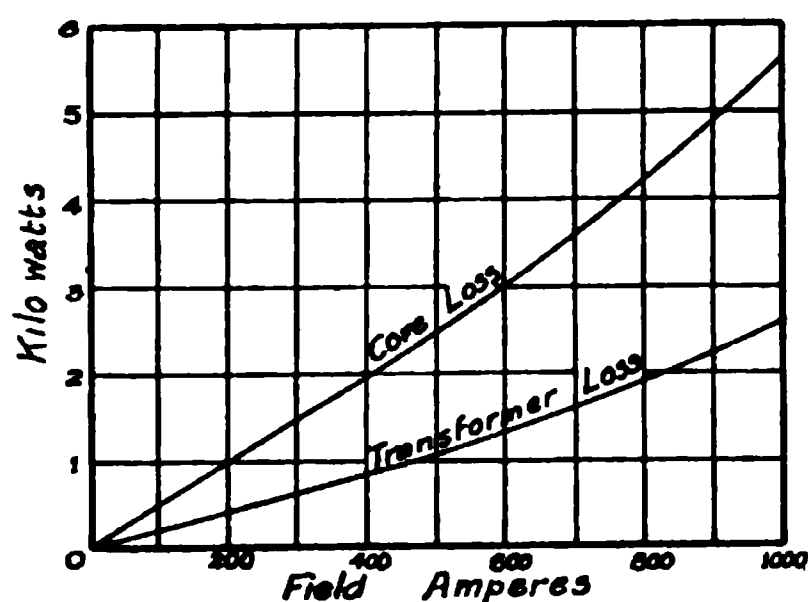


FIG. 105a.

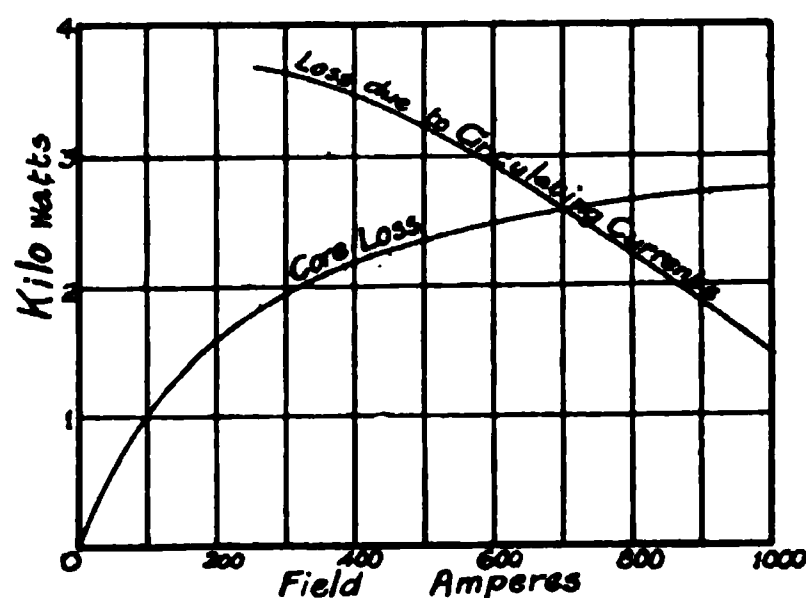


FIG. 105b.

Results of Core-loss Tests on Compensated-series Motor. NOTE.—The core-loss curve in Fig. 105a refers to the stator, while that in Fig. 105b refers to the armature.

has attained a constant value. Having decided the class of service (i.e. the schedule speed, stops per mile, and train weight per motor) an appropriate speed-time curve can be drawn, from which, in combination with the characteristic curves of the motor, the accelerating current; the time during which power is "on"; the coasting time, braking time, and duration of stop can be obtained.

A car equipped with motors and loaded to the required weight per motor is then operated on level track to this speed-time curve, the runs being continued until the temperature of the motors becomes steady. Additional tests are made for other service conditions, the motors being at the atmospheric temperature at the start of each test. The line voltage in all tests is maintained, as far as practicable, at the normal value. Provided that the service conditions, under which the tests are run, have been selected to give the same limiting temperature rise in each case, the service capacity can be obtained directly from the tests.

The determination of each service-capacity curve in this manner would consume too much time, as each test requires about 10 to 12 hours or more. Moreover, since any number of service-capacity curves can be calculated from the service thermal characteristics of the motor, it is

only necessary to perform sufficient tests to determine the latter curves. Thus, perhaps four or five tests under different operating conditions may be sufficient to enable these characteristics (and therefore the complete service capacity of the motor) to be determined.

The method by which the **service thermal characteristics** of the

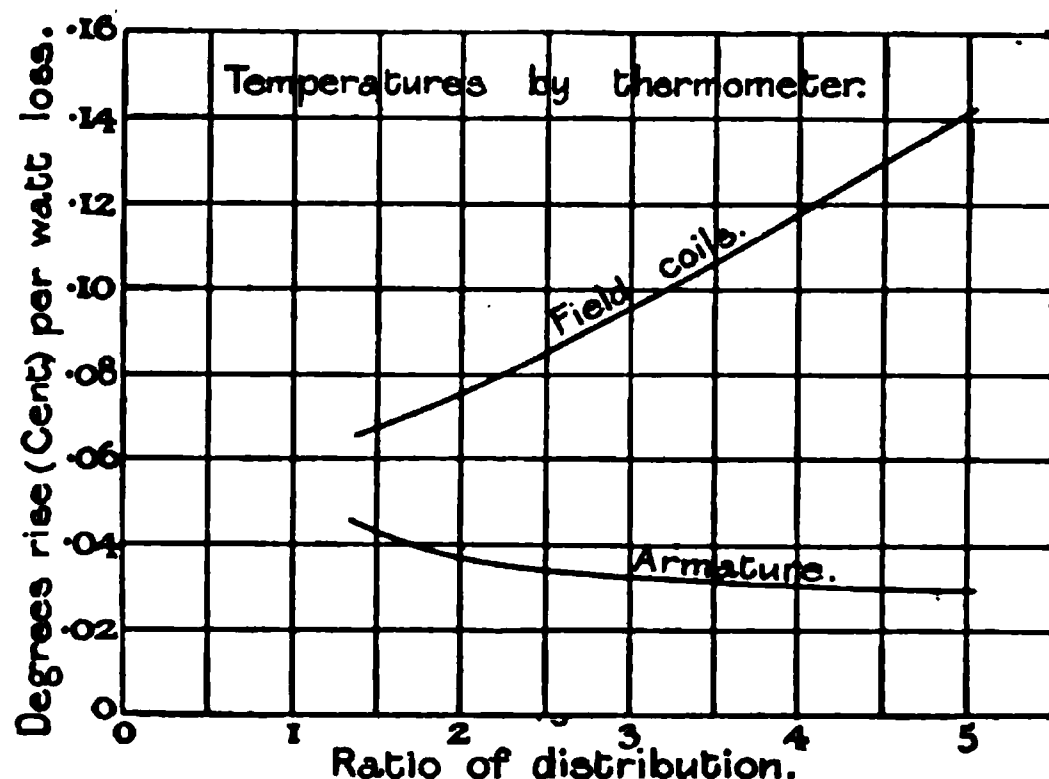


FIG. 106.—Thermal Characteristic of Railway Motor, showing the variation of the specific temperature rise with the ratio of distribution of losses, i.e. armature losses/field loss.

losses in the armature and field windings,* and, from the core-loss curves of the motor, we can obtain the core loss corresponding to the various values of current and voltage. In this manner the total loss in the armature and field of the motor is determined for a series of runs, and from the average losses and the final temperature measurements the **temperature rise per watt loss** for armature and field can be computed.

The **specific temperature rise** is usually expressed in terms of the ratio of distribution of the losses, i.e. the ratio of the armature loss to the field loss, as shown in Fig. 106. From these curves we can obtain a

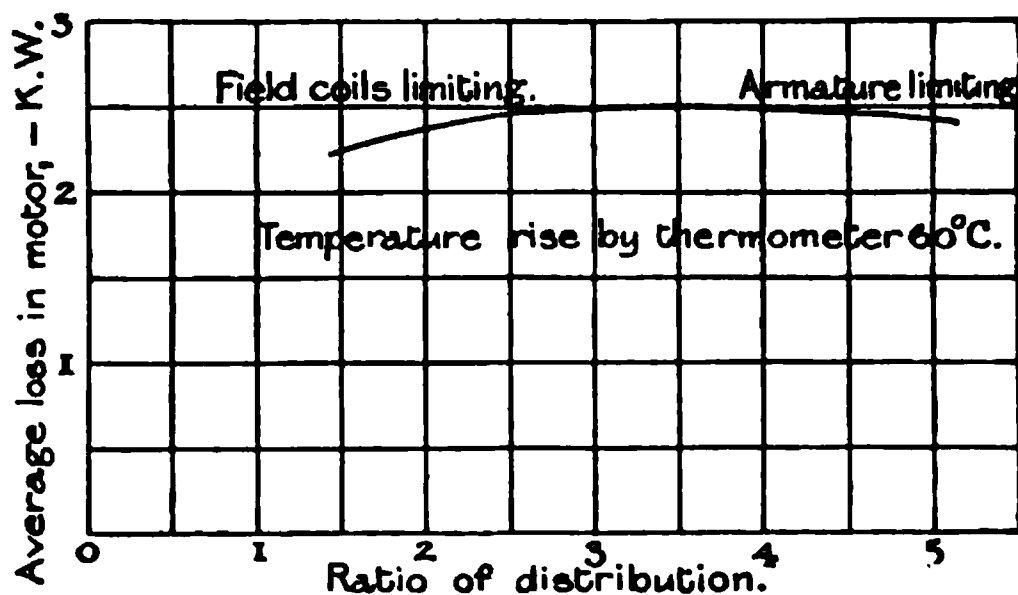


FIG. 107.—Service Thermal Characteristic of Railway Motor.

* In some cases the I^2R loss in the field coils has been determined directly, by means of an integrating wattmeter connected in the field circuit. The average loss is then obtained by dividing the watt-hours registered during the test by the duration of the test (in hours). If the average resistance of the field coils is also determined, the square of the average current during the test can be readily obtained, which, when multiplied by the average armature resistance, will give the average armature I^2R loss.

motors are determined from the above running tests is as follows: Records are obtained of the current and voltage, by means of suitable graphic-recording instruments, while the temperatures of the field and frame are observed at frequent intervals and the final temperatures of all parts are ascertained at the completion of the test.

The resistance of the field and armature windings are taken, if possible, during the lay-over periods. We are then able to calculate the I^2R

curve (Fig. 107) showing the total loss in the armature and field which will produce a definite maximum temperature rise.*

It will be observed that the maximum loss occurs with a certain ratio of the losses, and that at higher ratios the armature is limiting, while at lower ratios the field is limiting. The cause of this will be apparent after a little consideration, for the maximum loss must evidently occur when the temperature rises of the armature and field are equal to the maximum value. If the ratio of the losses is increased, the actual armature loss cannot be increased, as otherwise the temperature rise would exceed the permissible value, and hence the total losses must be lower.

In cases where tests of the above nature cannot be conducted, and it is required to test a pair of motors under running conditions (corresponding to the average cycle in service), the **fly-wheel brake test** can be adopted.† For this test two motors are geared to a shaft, on which are mounted one or more fly-wheels (representing the inertia of the car or train per pair of motors) and a brake (adjusted to represent the train resistance). Additional brakes, operated by compressed air, are fitted to the shaft for the purpose of stopping the set. The cycle of operations corresponding to service conditions, viz. starting, coasting, braking, &c., is performed automatically by a rotating master controller operating the contactor and air-brake circuits. The temperatures obtained from this test will differ somewhat from those obtained in actual service, on account of the conditions of ventilation not being equal in the two cases.

On “**official**” service tests it is necessary to determine the energy consumption, temperature rise of the motors, and schedule speed. With continuous-current equipments it is the practice to record the line voltage and the current input to one motor. With alternating current equipments, however, the input must be determined on the high-tension side of the main transformer by means of a wattmeter, while the current and line voltage must also be recorded in order to obtain the power-factor.

Graphic recording instruments for train testing must be designed

* In this connection, see a paper by Mr. F. W. Carter on “Technical Considerations in Electric Railway Engineering” (*Journal of the Institution of Electrical Engineers*, vol. 36, p. 231).

† A full description of this method of testing, and the apparatus used, is given in *The Electric Journal*, vol. 3, p. 702.

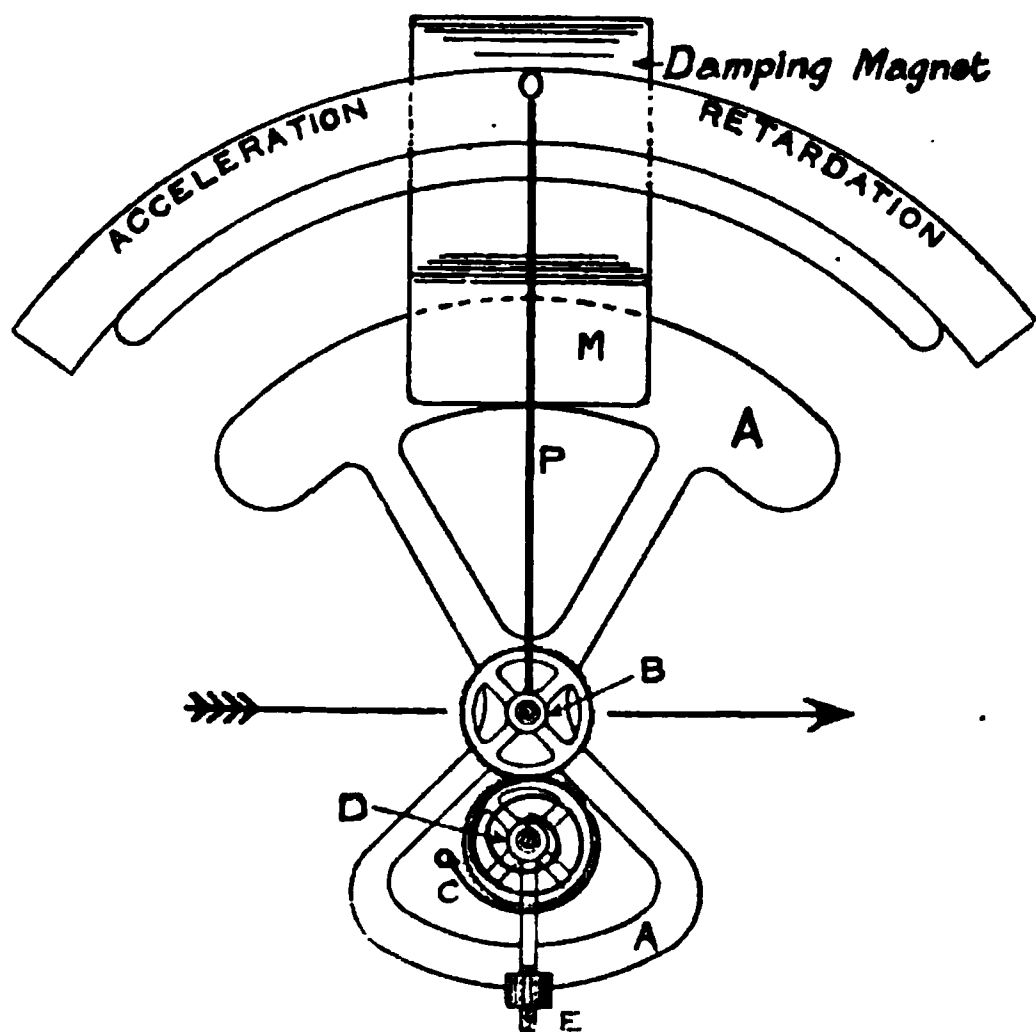


FIG. 108.—Diagram illustrating principle of Wimperis Accelerometer.

to withstand the large amount of vibration incidental to train operation, and are usually distinguished from the commercial forms of recording instruments by the high torque and large damping of the moving element.

These features are obtained in one type of continuous-current instrument by the use of a separately excited electro-magnet—instead of a permanent magnet—in conjunction with a relatively powerful moving-coil element which is damped by an eddy-current disc brake.

Time markers, operated by electro-magnets, are arranged to mark time intervals on the same paper as the current or voltage is recorded, and are actuated at five-second and one-minute intervals from a special clock.

The **speed** may be obtained either indirectly, by actuating one of the markers from a contact fixed to the car axle, or directly, by means of a special magneto generator—driven from the axle—in conjunction with a recording voltmeter.

With the introduction of a reliable instrument for the **direct measurement of acceleration and retardation**, it is now the practice to determine these quantities directly, instead of relying on the speed record. The instrument used for this purpose is usually the **Wimperis accelerometer**, which is made in both the indicating and recording types.

FIG. 109.—Wimperis Indicating Accelerometer (Elliott Bros.).

In each type of instrument the moving element consists of an aluminium sector *A* (Fig. 108) fixed to a spindle *B*, which is mounted vertically in jewelled bearings. Since the centre of gravity of the sector is not coincident with the axis of rotation, any force resulting from acceleration will cause a rotation of the spindle and a deflection of the pointer *P*, provided that the direction of the force is not in the plane containing the centre of gravity and the axis. The rotation of the spindle *B* is restrained by a hair-spring *C*, fixed to another spindle *D*, which is geared to the former spindle by 1 : 1 gearing. The spindle *D* also carries a compensating balance-weight *E*, which is adjusted to have a moment of inertia equal to that of the sector and pointer, the centre of gravity of the sector and compensating balance-weight being contained in a plane passing through *D* and *B*. In this manner the sector and compensating balance-weight will have equal and opposite moments about the spindle *B* in a direction at right angles to the motion. The instrument is therefore only affected by accelerating forces which have a component along the direction of motion, and it is eminently suited for train testing.

A view of the indicating type of instrument is given in Fig. 109.

CHAPTER VIII

THE CONTROL OF CONTINUOUS-CURRENT TRAMWAY MOTORS

IN Chapter III we have shown that, during the initial period of acceleration of a train or tramcar, the tractive-effort exerted by the motors is considerably greater than that exerted during the remaining period of the run. For approximate purposes the tractive-effort during the period of initial acceleration may be taken as that corresponding to the rated load of the motors. Therefore each motor will require practically full-load current throughout the starting period.

Tramcars are always equipped with two motors, and the motor-coaches of electric trains are equipped with either two or four motors (see Chapter XVI). Hence, if the motors were permanently connected in parallel and controlled by a starting rheostat, a large amount of energy would be wasted in the latter, and for the conditions under which tramways and urban railways operate, this energy would form a large percentage of the total energy input. It is necessary, therefore, to ascertain if a more economical method of control could be adopted.

Now the torque developed by a continuous-current motor depends only on the product of the armature current and the magnetic flux. In the case of a series motor, supplied with constant current, the torque will be constant, and the speed will be proportional to the counter-E.M.F., or approximately proportional to the voltage at the terminals of the motor.

Hence, if we have two similar series motors to be started, we may arrange them in series for the first half of the starting period, and in parallel for the second half of this period. If the current per motor is maintained at a constant value throughout the starting period, the energy output will be exactly the same as that which would have been obtained, under similar conditions, with the motors permanently connected in parallel. The energy input, however, will be considerably lower.

With the motors in series and all the starting rheostat cut out, the speed of each motor will be slightly less than one-half of that corresponding to the same current per motor at full voltage (*i.e.* with the motors in parallel).

This method of control—called the **series-parallel system**—is, therefore, suitable for tramways and railways, since not only are two economical speeds available, but the overall efficiency during starting is much higher than that of the plain rheostatic method. Thus, if we assume the current in each motor to be maintained at a constant value through-

out the starting period, the total torque developed by the motors will be constant, and will not be affected by the series or parallel connection of the motors. When the motors are in series, their counter-E.M.Fs. are also in series; so that, for a given consumption of energy, the work done during this (series) portion of the starting period will be twice that obtained from one motor started by the rheostatic method.

Hence the economy of the series-parallel system of control results from the *series connection of the motors*, since, in the parallel connection, the conditions correspond to the rheostatic method of starting.

This point is further elucidated by the diagrams of Figs. 110, 111. The diagrams of Fig. 110 show the variation of the currents and voltages during the starting period, when two similar series motors are started by the rheostatic (parallel) and series-parallel methods respectively, while the diagrams of Fig. 111 show the distribution of the

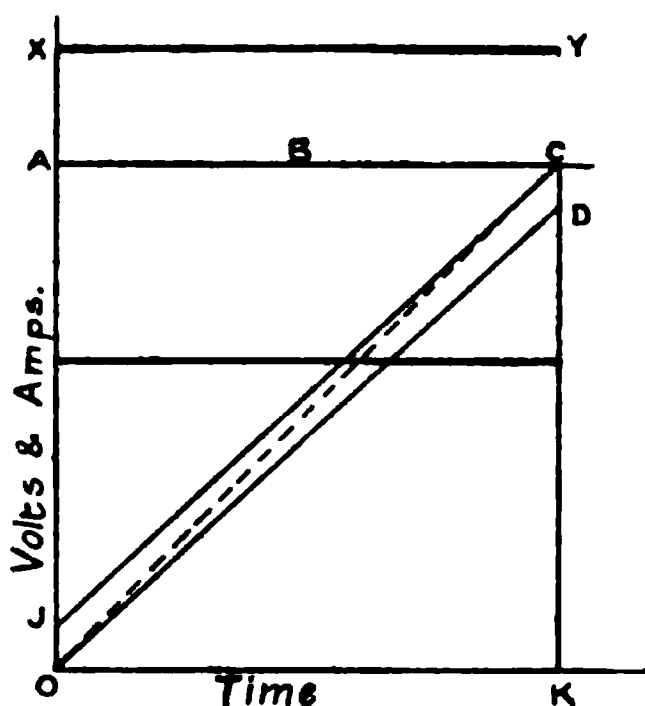


FIG. 110a.

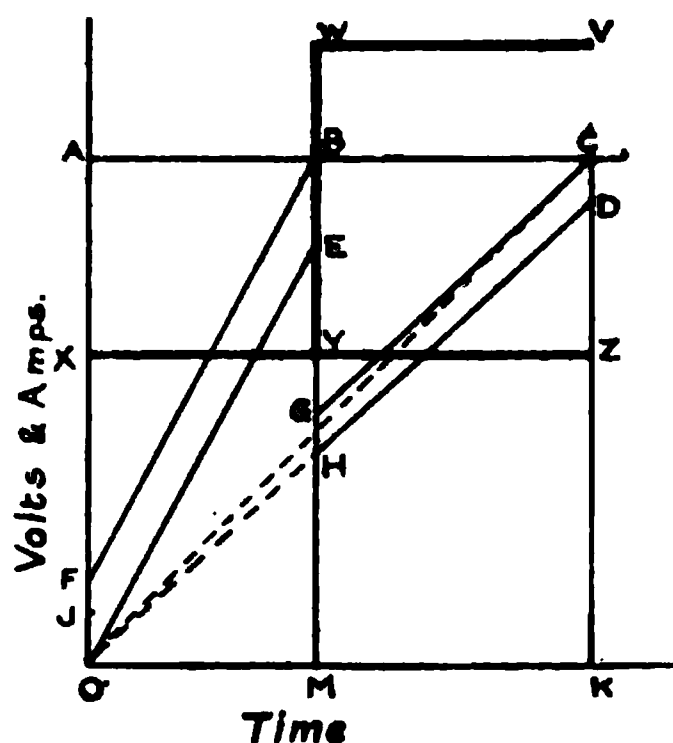


FIG. 110b.

energy in the two cases. The diagrams have been drawn for ideal starting conditions—i.e. for a constant current per motor and constant line voltage—and, in Fig. 111, only the I^2R losses in the motors have been considered.

Referring to Fig. 110a, the line (or supply) voltage is represented by ABC , the line current (which in this case is twice the motor current, since the motors are in parallel) by XY , and the voltage drop in the motors by OJ (or CD). Hence JC represents the variation of the voltage at the terminals of the motors, and OD represents the variation of the counter-E.M.F. during the starting period. The energy input from the supply system will be given by—(line current \times line voltage \times time), and is represented, in Fig. 110a, by the area $OACD$; while the energy utilised in the two motors will be given by—2 (current per motor \times average value of counter-E.M.F. \times time), and is represented, in Fig. 110a, by the area OFD .

Referring to Fig. 110b, the current per motor is represented by XYZ , and the line current by $XYWV$, of which XY refers to the line current when the motors are in series, and WV refers to the line current when the motors are in parallel. Since the current per motor is assumed to be constant throughout the starting period, the counter-E.M.F. per motor must increase uniformly with time. The counter-E.M.F. at the

end of the starting period (i.e. when the motors are in parallel) is represented by DK , so that OD must represent the variation of the counter-E.M.F. per motor during the starting period. When the motors are in series with all the starting rheostat cut out, the total counter-E.M.F. plus the total voltage drop in the motors must equal the line voltage.

These conditions enable us to determine the times of the two portions of the starting period. It should be noted that the duration of the first (or series) portion is slightly less than that of the second (or parallel) portion.*

The energy input to the two motors during the starting period will be given by—(average line current \times line voltage \times time), and is represented, in Fig. 111b, by the area $OABB'CD$; while the energy utilised in the motors will be given by—2 (current per motor \times average value



FIG. 111a.



FIG. 111b.

of counter-E.M.F. \times time), and is represented, in Fig. 111b, by the area $OAB'CD$, which is equal to the area OFD in Fig. 111a.

If the internal resistances of the motors be neglected, then the variation of the counter-E.M.F. per motor during the starting period will be given by OC (Fig. 110). With this simplification, it is apparent (from Fig. 111) that, with series-parallel control, the total loss in the rheostats is only one-half of that with plain rheostatic control. Moreover, with plain rheostatic control, the loss in the rheostats is equal to the energy utilised in the motors. Thus it follows that the average efficiency during the starting period is 50 per cent. with rheostatic control and 66.6 per cent. with series-parallel control.

We can extend the series-parallel system to four motors, and obtain still greater economy in starting by dividing the starting period into three portions, in which the motors are respectively connected (1) in

* If T denotes the total time of the starting period, t_s , t_p , the times of the series and parallel portions, V , the line voltage and v the voltage drop per motor, then from similar triangles OHM , ODK (Fig. 110b) we have

$$\frac{t_s}{T} = \frac{HM}{DK} = \frac{\frac{1}{2}V - v}{V - v};$$

whence

$$t_s = \frac{T}{2} \left(\frac{V - 2v}{V - v} \right), \text{ and } t_p = T \left(1 - \frac{1}{2} \left(\frac{V - 2v}{V - v} \right) \right).$$

series, (2) in series-parallel, and (3) in parallel. We will call this method the **double series-parallel system**. This system is only adopted in practice to a limited extent on account of the increased complication of the control apparatus, and, even when four motors are available, they are usually controlled on the series-parallel system. The allocation of the energy in the double series-parallel system of control is indicated in Fig. 112, which, on examination, will show that the energy consumption is only 8.33 per cent. less than that of the series-parallel system applied to the same equipment.

The various combinations of the motors and rheostats are made in the correct order by a **controller**. On tramways the controller is of the drum type. This type of controller consists of a drum or cylinder carrying a number of insulated (and interconnected) segments, which can make contact with a number of fixed contacts (or fingers) to which the motors and rheostats are connected. The drum can be rotated through certain angles, and in each position (except the "off" position) connections are

W
e
b
s
t
e
r

A

E

O

FIG. 112.

made between certain fingers, thereby effecting certain combinations between the motors and rheostats.

In addition to starting and regulating the speed of the motors, a tramcar controller has to be arranged so that—

- (1) The car can be operated in either direction of motion;
- (2) The motors can be used for electric braking; and
- (3) The car can be operated if one motor becomes disabled.

The construction of such a controller is therefore complicated, but, by considering how each requirement is fulfilled, we hope to show that the complication is only the result of the aggregation of several devices in one casing.

Let us first consider a controller for the control of a series motor operating in one direction of rotation. Fig. 113 shows the development of the segments of a controller for this purpose. The fingers are represented by the vertical row of large dots, and the segments are shown to the right. The operating positions (or "notches") of the segments are indicated by the vertical dotted lines, numbered 1 to 5, which coincide with the centre-line of the fingers in the operating positions of the controller cylinder. Thus on the first notch (No. 1) the top and second fingers are connected together, thereby connecting all the starting rheostat in the motor circuit. Sections of the starting rheostat are cut out on the successive notches, until, on the last notch (No. 5), the motor is connected directly to the line. Notch No. 5 is therefore called a *running position*, while the other notches (1 to 4) are called *rheostatic positions*.

If the motor is required to be operated in each direction of rotation,

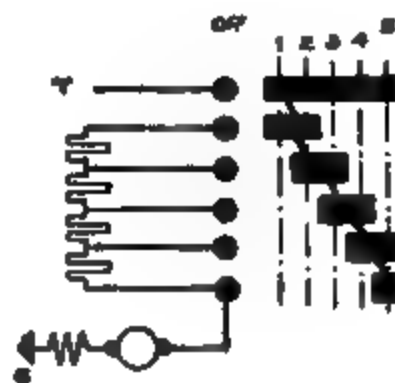


FIG. 113.

then we must use either an external reversing switch with this controller, or a **reversing controller** (i.e. one with a separate set of segments for each direction of rotation of the motor). A controller of this type is illustrated in Fig. 114, the development, connections, and combinations being shown in Fig. 115, in which the method adopted for reversing the motor should be noted.

Now consider the **control of two motors on the series-parallel system**. We have now to arrange that the motors shall be started up in series and changed into parallel without subjecting either motor to excessive voltage. Obviously, the simplest manner of accomplishing this is to open the entire circuit after the last series notch, change the connections to parallel, and re-connect the motors to the supply with the correct resistance in circuit. The development of a controller cylinder to fulfil these requirements is indicated in Fig. 116a, the combinations of motors, &c., being shown in Fig. 116b.

The disadvantages of this method are (1) that the propelling power is removed from the car during the transition period, and (2) that the total current must be broken in the controller. A reference to Fig. 116a will show that there are only four breaks in series. Hence, with a line voltage of 500 volts, the voltage at each break will be 125 volts, which, with the full load current of the motors, will require a powerful magnetic blow-out to prevent burning of the fingers and segments. This method of transition has been used to some extent on tramways and railways, but it is now superseded by the methods described below.

FIG. 114.—B.T.-H. Rheostatic Controller for Reversible Motor.

There are two **methods of transition from series to parallel whereby the main circuit is not opened**, these methods being known as (1) the short-circuited-motor method, and (2) the "bridge" method. The former method is standard with all modern tramcar controllers, while the latter method is used in controllers for electric railways.

In making the transition by the first method, it is necessary to insert some resistance into the circuit before short-circuiting the motor, in order to avoid an excessive rise of voltage on the other motor. The short-circuit is opened at another point, so that the power circuit is not interrupted, and the second motor is then connected in parallel with the first. The development, connections, and combination diagrams for a controller in which this method of transition is used are shown in Fig. 117.

The **bridge method of transition** is generally adopted on railways with multiple-unit (remote) control systems, as described in Chapter IX. The method has also been applied to smaller equipments with direct control, and, for the purpose of comparing these controllers with those for the above methods of transition, we give in Fig. 118 the develop-

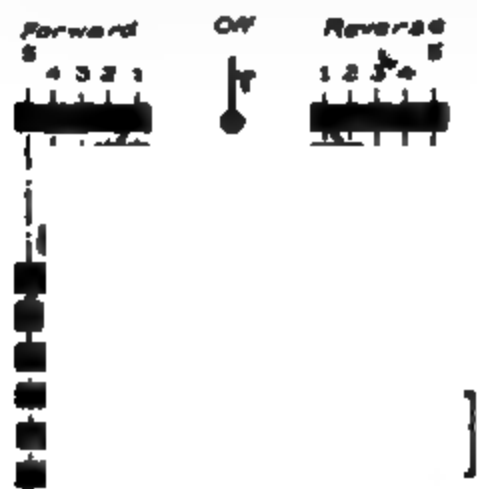


FIG. 115a.

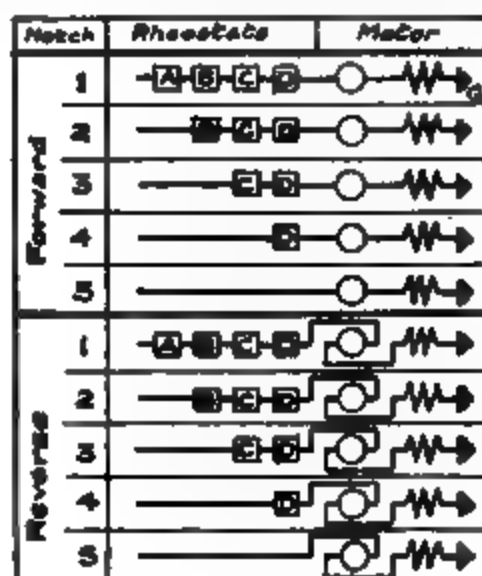


FIG. 115b.

Connections, Development, and Combinations for Reversing Rheostatic Controller

ment, connections, and combination diagrams for a controller with bridge transition.

It will be observed that the rheostats are divided into two groups, one group for each motor. The resistance sections of each group are cut out simultaneously in the usual manner until the last series point is reached. The first transition point inserts the "bridge" connection and opens the short-circuits between the resistance sections, as indicated

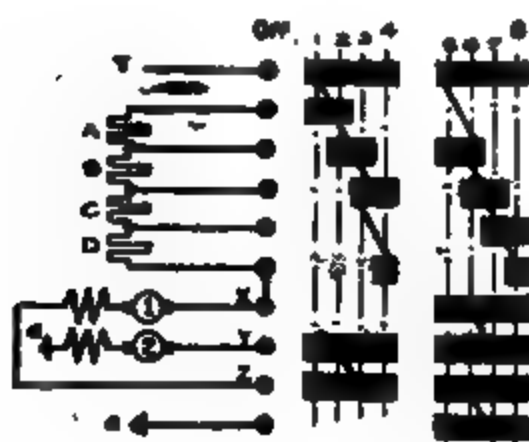


FIG. 116a.

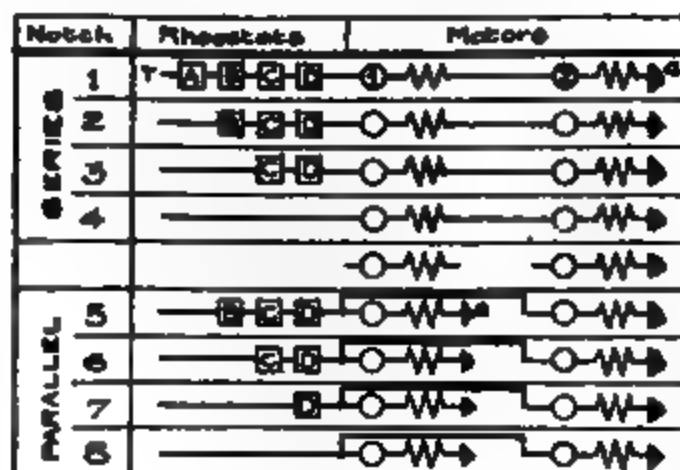


FIG. 116b.

Connections, Development, and Combinations for Series-parallel Controller (open-circuit transition).

in greater detail by the diagrams *A* and *B* of Fig. 119. The rheostats are now connected directly to the supply (see Fig. 119, Diagram *C*), and if the current passing through the rheostats is equal to the current taken by the motors, then the connection *X* may be opened without subjecting the motors to any increase of voltage. But, by the opening of this

connection, each motor, with its corresponding rheostat, is connected across the supply, and the motors are therefore in parallel. Thus the transition has been effected without opening the circuit or short-circuiting a motor. Moreover, *the full accelerating current has been maintained on each motor during the transition period.* The bridge method of transition is therefore advantageous for services which require a high sustained acceleration.

Reversing Cylinder.—Since a tramcar has occasionally to be driven in both directions from one controller, the device for reversing the motors may be operated separately from the main cylinder of the controller. The device usually takes the form of a small cylinder with segments which make contact with a set of fixed fingers, to which the armature and fields leads are connected. The reversing cylinder is interlocked with the main cylinder, so that it cannot be operated until the latter

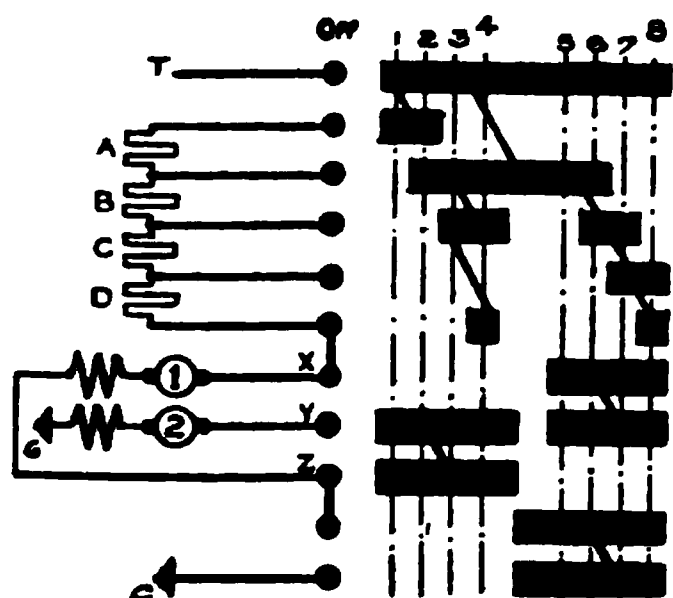


FIG. 117a.

Notch	Rheostats	Motors
SERIES	1	T-A-B-C-D-①-W-②-W-G
	2	-B-C-D-O-W-O-W-→
	3	-C-D-O-W-O-W-→
	4	-O-W-O-W-→
PARALLEL	5	-B-C-D-O-W-→-O-W-→
	6	-C-D-O-W-→-O-W-→
	7	-O-W-→-O-W-→
	8	-O-W-→-O-W-→

FIG. 117b.

Connections, Development, and Combinations for Series-parallel Controller (short-circuited-motor transition).

is in the “ off ” position. To reverse a motor by this method we require four fingers with two sets of contacts, interconnected as in Fig. 120, A.

With two motors, eight fingers would be required, which may be arranged either in one line, as in Fig. 120, B, or on each side of the reversing cylinder, as in Fig. 120, C.

Electric Braking.—In this country the larger tramway systems use magnetic track brakes for service stops, and, even when track brakes are not fitted to the cars, it is standard practice to arrange the controller for electric braking. In both cases the motors are operated as series generators (being driven by the momentum of the car), and the current generated is dissipated in the rheostats and brakes.

The motors are *always connected in parallel for electric braking*, since the series connection would produce too high a voltage, and would require an excessive resistance for regulating the braking effect.

The brake is applied by moving the controller handle, beyond the off position, in the opposite direction to that when power is being supplied to the motors.

In order that the motors may “ build up ” as generators, it is necessary to reverse the connections between the armatures and field windings. In some of the older types of controllers this was accomplished

by mechanically operating the reversing cylinder when the main cylinder was moved to the braking notches, but this method has been abandoned in favour of that in which a separate set of fingers and segments on the main cylinder is used, as indicated in Fig. 121.

In connecting the motors in parallel for electric braking, we must either use an *equalising connection* between the brushes, as shown in Fig. 122a, or *cross-connect the motors*, as shown in Fig. 122b.

The equalising connection is necessary in order that each machine may take its proper share of the load, since, if it were omitted, the machine which excited first would demagnetise the other and reverse its E.M.F. The machines would then be in series and short-circuited. A large current would circulate through the machines and thereby pro-

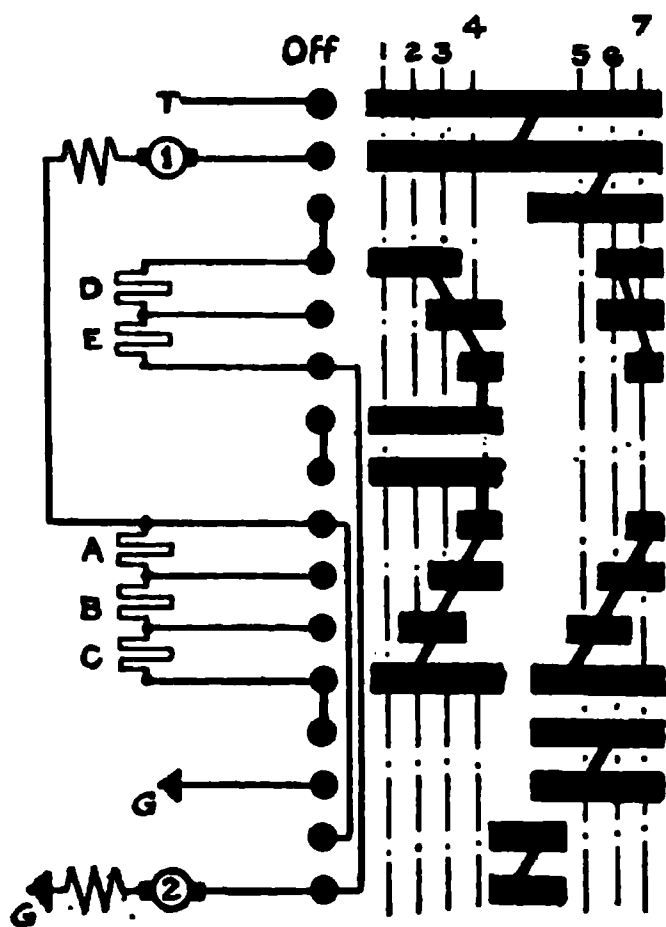


FIG. 118a.

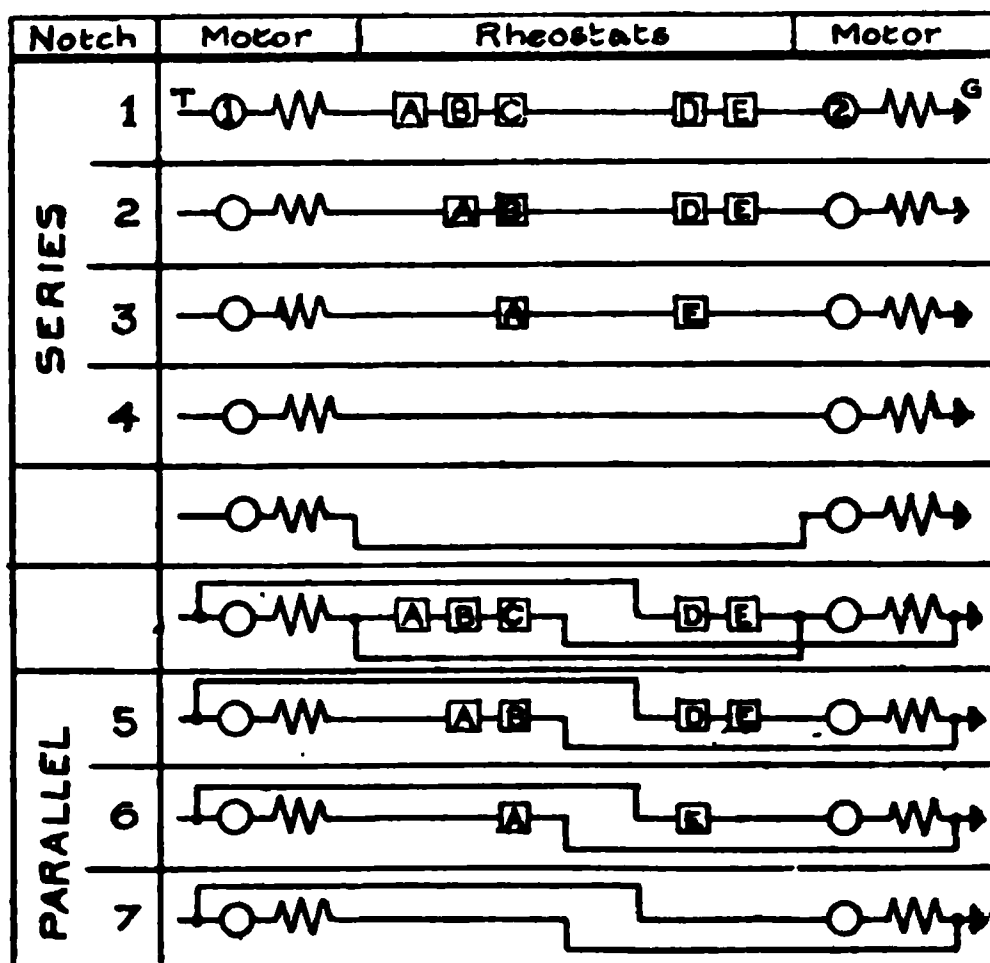


FIG. 118b.

Connections, Development, and Combinations for Series-parallel Controller (bridge transition).

duce a very powerful braking effect, over which the motorman would have no control.

In controllers in which this method is used for braking, it is essential that the position of the reversing cylinder corresponds to the motion of the car, otherwise the motors will not excite. Hence, if a car runs backwards down-hill, the reversing cylinder must be thrown to the "reverse" position before the electric brake can become operative.*

With the motors cross-connected, as in Fig. 122b, electric braking can be obtained in *either direction of motion of the car without operating the reversing cylinder*. Under normal conditions the machines operate as generators in parallel, and the direction of the current in various parts of the circuit is represented, in Fig. 122b, by the arrows. If the direction of rotation of both machines is reversed and the connections are unaltered, the machines will "build-up" as generators in series,

* It should be remarked that an electric brake depending on the rotation of the motor armatures cannot "hold" a car on a hill, but it will prevent the car from "running away." For holding a car on a hill, mechanical brakes are necessary.

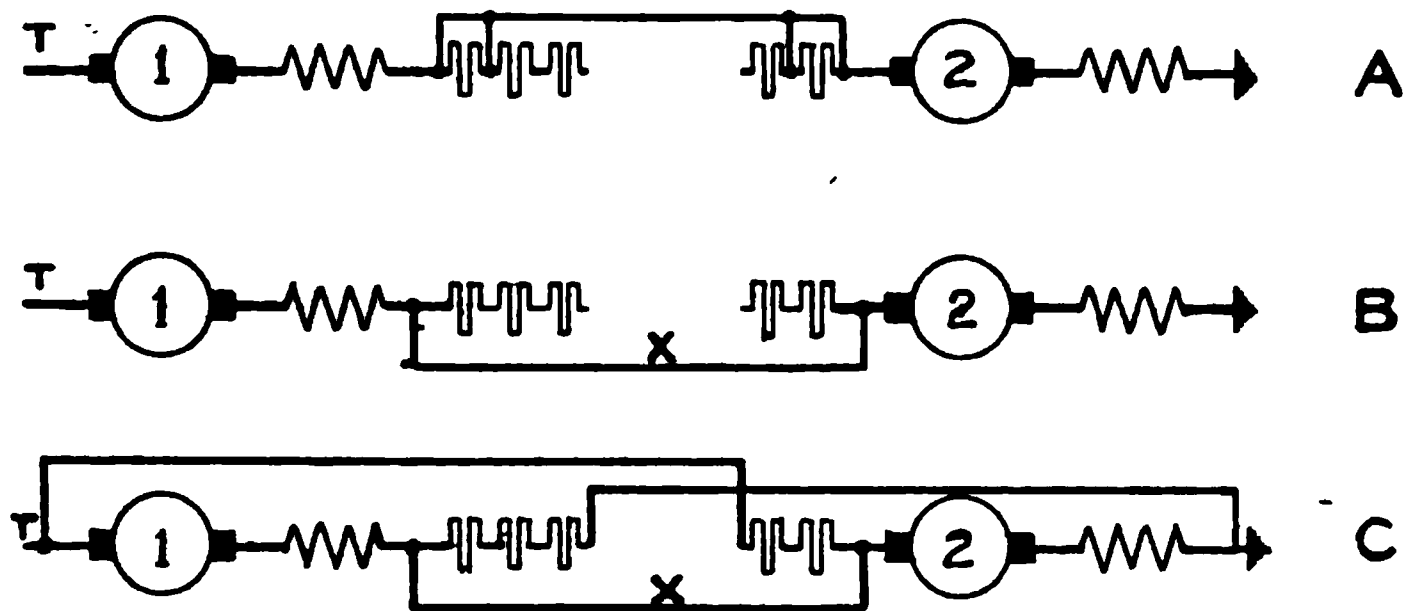


FIG. 119.—Transition Steps for Fig. 118.

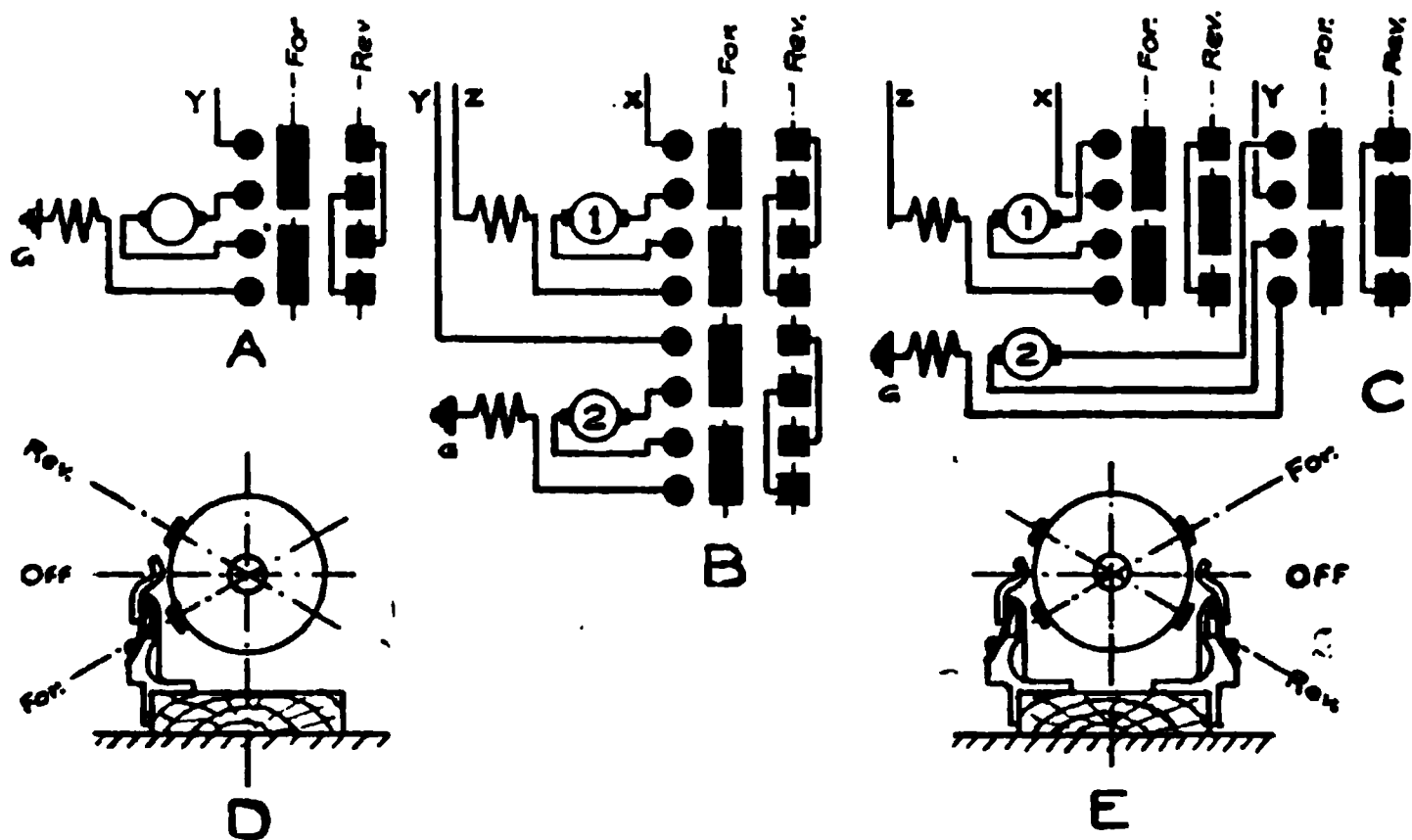


FIG. 120.—A, B, C, Connections and Development of Reversing Cylinders. (NOTE.—Leads X, Y, Z are connected to fingers of main cylinder—see Figs. 116a, 117a.) D, E, End-elevation of Reversing Cylinders showing relative positions of segments and fingers.

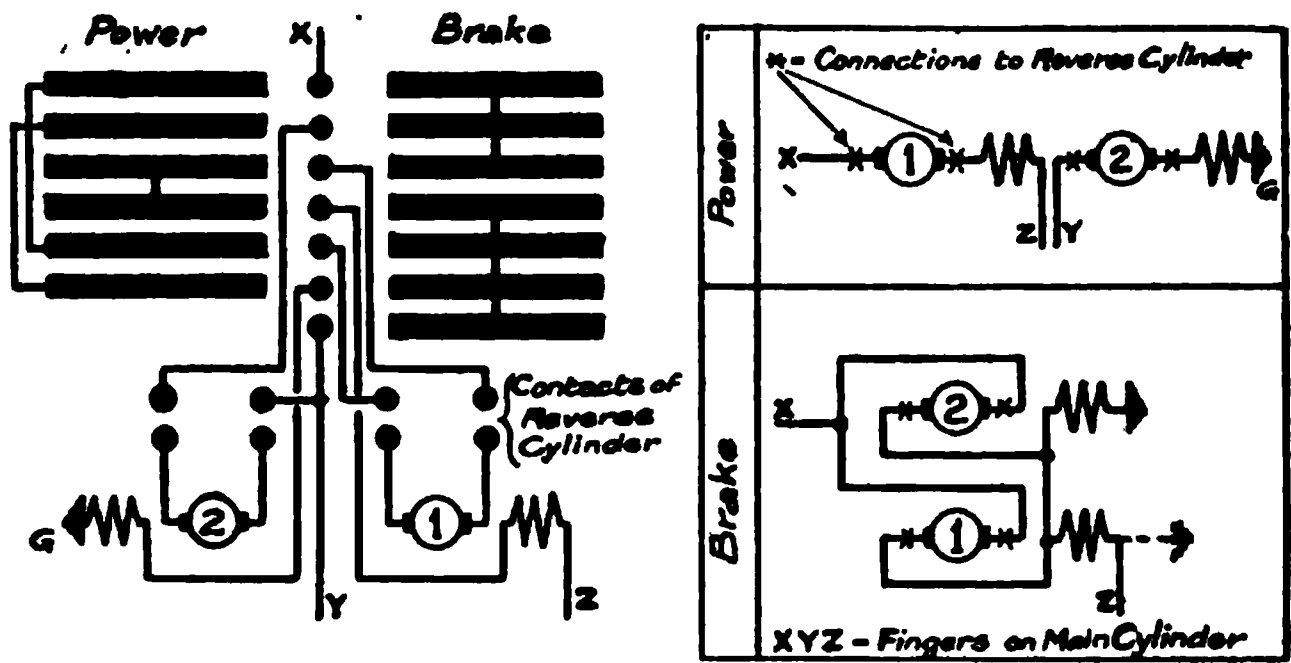


FIG. 121.—Connections, Development, and Combinations of Brake Cylinder of Series-parallel Controller.

and will be short-circuited on each other, thereby producing a powerful braking effect. The condition upon which this result depends is that the residual magnetism of the machines must be unequal, and this

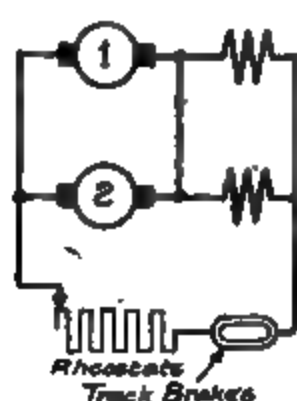


FIG. 122a.

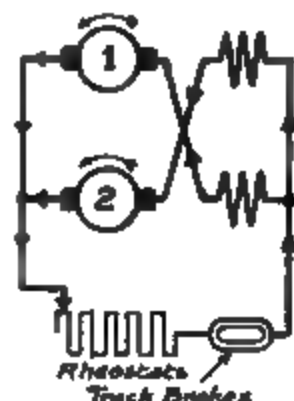


FIG. 122b.

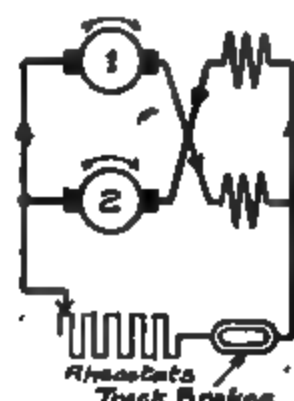


FIG. 122c.

Methods of Connecting Motors for Electric Braking.

condition is usually fulfilled in practice. Thus, consider machine No. 1 (Fig. 122c) to have the larger residual magnetism. A current will then circulate between the machines in the direction shown in Fig. 122c.

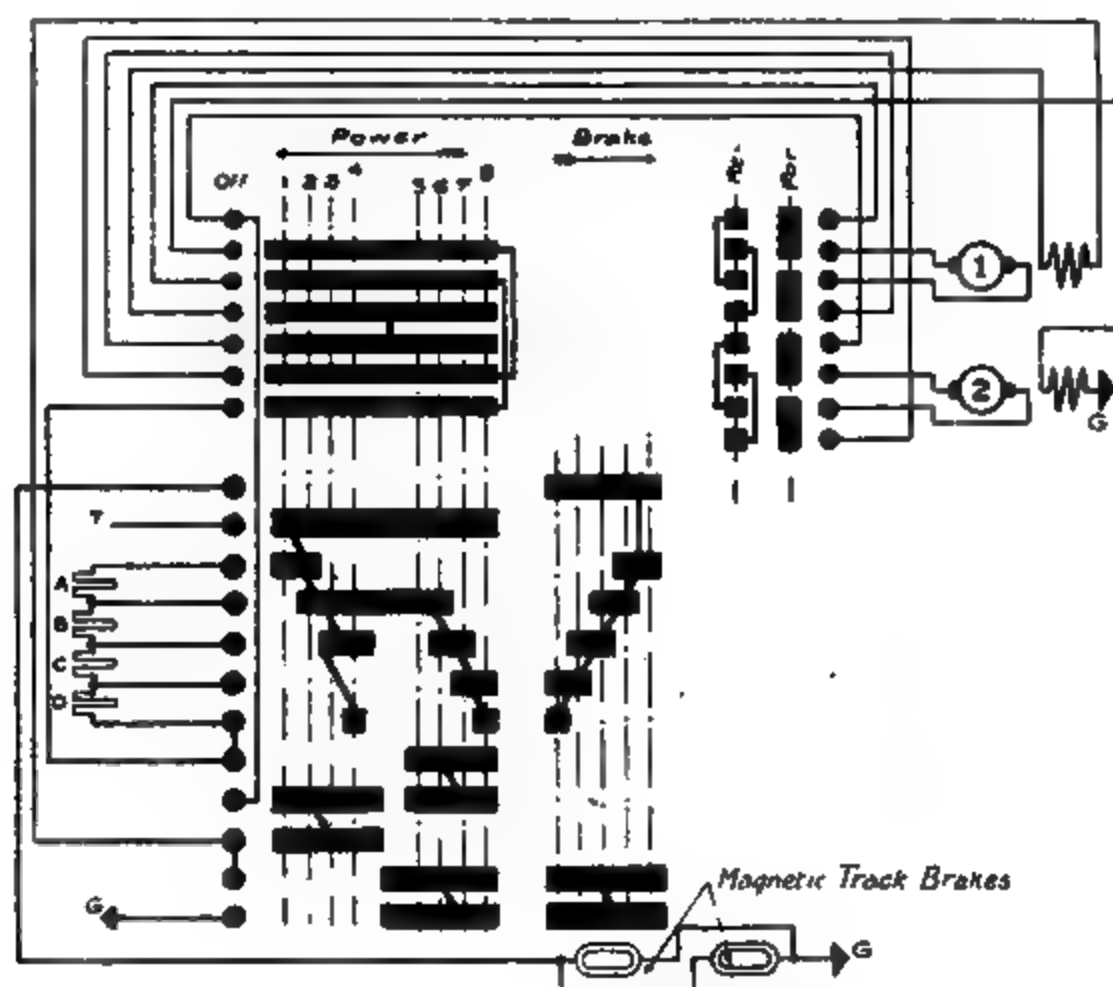


FIG. 123.—Connections and Development of Series-parallel Controller with Electric Brake.

which will demagnetise machine No. 2 and excite machine No. 1. The field of No. 2 will then be reversed, and it will now excite and add its voltage to No. 1, thereby causing a short-circuit.

In Fig. 123 we have a diagram of the connections and development of a series-parallel controller with electric braking. This diagram is the result of combining Figs. 117, 120, 121, and represents the simplest case of a series-parallel controller arranged for electric braking.

The diagrams of actual controllers will, of course, be much more complicated, due to (1) the provision of a larger number of notches on the braking side, (2) the device for cutting-out a defective motor, (3) the necessity for providing a magnetic blow-out on the fingers and segments where current is broken.

The device for cutting-out a defective motor may take the form of (a) additional segments on the reversing cylinder, (b) special fingers which can be raised from the segments, (c) double-throw switches on the terminal board of the controller. The arrangement of these devices in actual controllers is described below.

The function of the magnetic blow-out is to provide a magnetic field of such strength that the arc formed between the fingers and segments shall be suppressed before it can damage the contacts. In all controllers the magnetic field is provided by an electro-magnet or solenoid, but the arrangement of the magnetic circuit differs considerably in controllers of different types.

The simplest form of magnetic blow-out is found in controllers of the type illustrated in Fig. 114. In these controllers a flux, perpendicular to the shaft, is produced in the vicinity of the fingers, so that any arcs forming between fingers and segments will be blown in a direction parallel to the shaft. In order to prevent an arc striking adjacent fingers, the latter are separated by barriers, or "arc deflectors," of fire-proof material, which can be swung clear of the fingers and segments (see Fig. 114). The arc deflectors are fixed to a hinged iron bar which, normally, forms one pole of an electro-magnet, the other pole being formed by the shaft. The exciting coil, through which the main current passes, is concentric with the shaft, and is located at its lower end.

This type of blow-out (which may be called the "shaft" type) is only suitable for controllers handling small currents, and is not adopted on tramcar controllers. It is, however, adopted on some types of master controllers for electric railways. The types of blow-out adopted on tramcar controllers will be considered in the descriptions of tramcar controllers given below.

TYPICAL MODERN TRAMCAR CONTROLLERS

B 49 Controller of the British Thomson-Houston Co.—This controller is provided with an externally-operated cut-out device—by means of which either motor may be cut-out without opening the controller—and is arranged so that electric braking can be obtained, with the car moving either forwards or backwards, by the single movement of the main handle to the braking notches.

Fig. 124 illustrates an interior view of this controller, while Fig. 125 shows the top of the cap-plate with the operating handles in position. In this view the cut-out spindle and the various "notches" can be clearly seen, there being four series notches, four parallel notches, and

seven brake notches on the main cylinder, as well as the "forward" and "reverse" notches on the reversing cylinder, and the "cut-out" notches.

The controller-back is of cast iron, and carries the bearings for the shafts, seatings for finger-boards, and the core of the blow-out magnet.

To the upper portion of the main shaft is fixed a cylinder *B* (called the "brake cylinder") carrying a set of segments, which, with the corresponding seven fingers, provides the means for reversing the connections of the motors between "power" and "brake." Below the brake cylinder we have the "main cylinder," constituted of a number of segments which are arranged in three sections— C_1 , C_2 , C_3 —insulated from one another and from the shaft. These segments, with the corresponding set of fourteen fingers, are arranged to give the correct combinations of the motors and rheostats on each operating notch. Each section of segments consists of two brass castings, which are clamped to a square portion of the shaft and insulated therefrom with moulded mica. The castings are provided with suitable projections to which the copper segments are fixed.

FIG. 124.—B.T.-H. (Type B 49)
Controller.

The main fingers are attached to brass finger-bases, screwed to a finger-board of treated ash, which is fixed to the controller-back. Typical fingers and finger-bases are shown in detail in Fig. 126. Pressure between the fingers and segments is obtained by

FIG. 125.—Cap-plate of B 49 Controller with
handles in position.

FIG. 126.—B.T.-H. Controller Fingers.



FIG. 127.—Arc-deflector Plates of B 49 Controller.

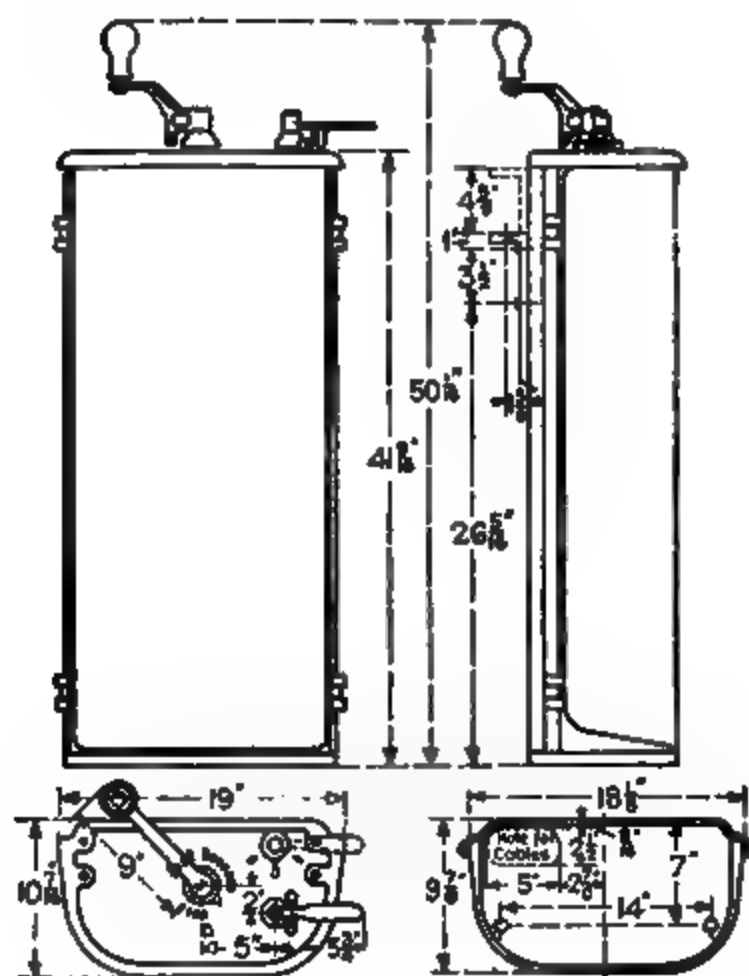


FIG. 128.—Dimensions of B 49 Controller.

means of a flat spring, and is adjusted by a set-screw. The fingers on the brake and reversing cylinders are of lighter construction than those on the main cylinder, since each finger has only to carry the current of one motor and no current has to be broken.

The magnetic blow-out is of the "pole-piece" type. Each of the main fingers is enclosed between arc deflector plates *D*, of fireproof material, which are fixed to the hinged cast-iron pole-piece *P*. When

FIG. 129.—Connections and Development of B 49 Controller (B.T.-H. Co.).

closed, the upper part of this pole-piece is bolted to the pole-core *Q*, forming part of the controller-back. The pole-core is surrounded by the blow-out coil *S*, which is energised whenever current is passing in the motor circuit. We therefore have a flux produced in the vicinity of the fingers, the direction of the flux being perpendicular to the shaft, and any arc between fingers and segments will be blown either upwards or downwards (depending on direction of the current and the flux) on to the deflector plates.

The deflector plates are illustrated in detail in Fig. 127.

The reversing cylinder *R*₁, *R*₂ possesses especial interest, since it

fulfils the double function of reversing the direction of motion of the car and of cutting out a defective motor. It is constructed in two sections—one for each motor—with the segments arranged as shown in the development diagram (Fig. 129). Each section is not permanently fixed to the reversing spindle, but either or both sections may be locked to the spindle as desired, the locking being accomplished by a mechanical device operated by the cut-out spindle. The latter is operated by applying the reversing handle to it, but the reversing handle can only be removed from the spindle of the reversing cylinder when the latter is in the “ off ” position.

The **cut-out spindle** has three positions, viz. a central position, in which both motors are in circuit, and a position on each side of the central position, in which only one motor is in circuit. When in the central position—as shown in Fig. 125—both sections of the reversing

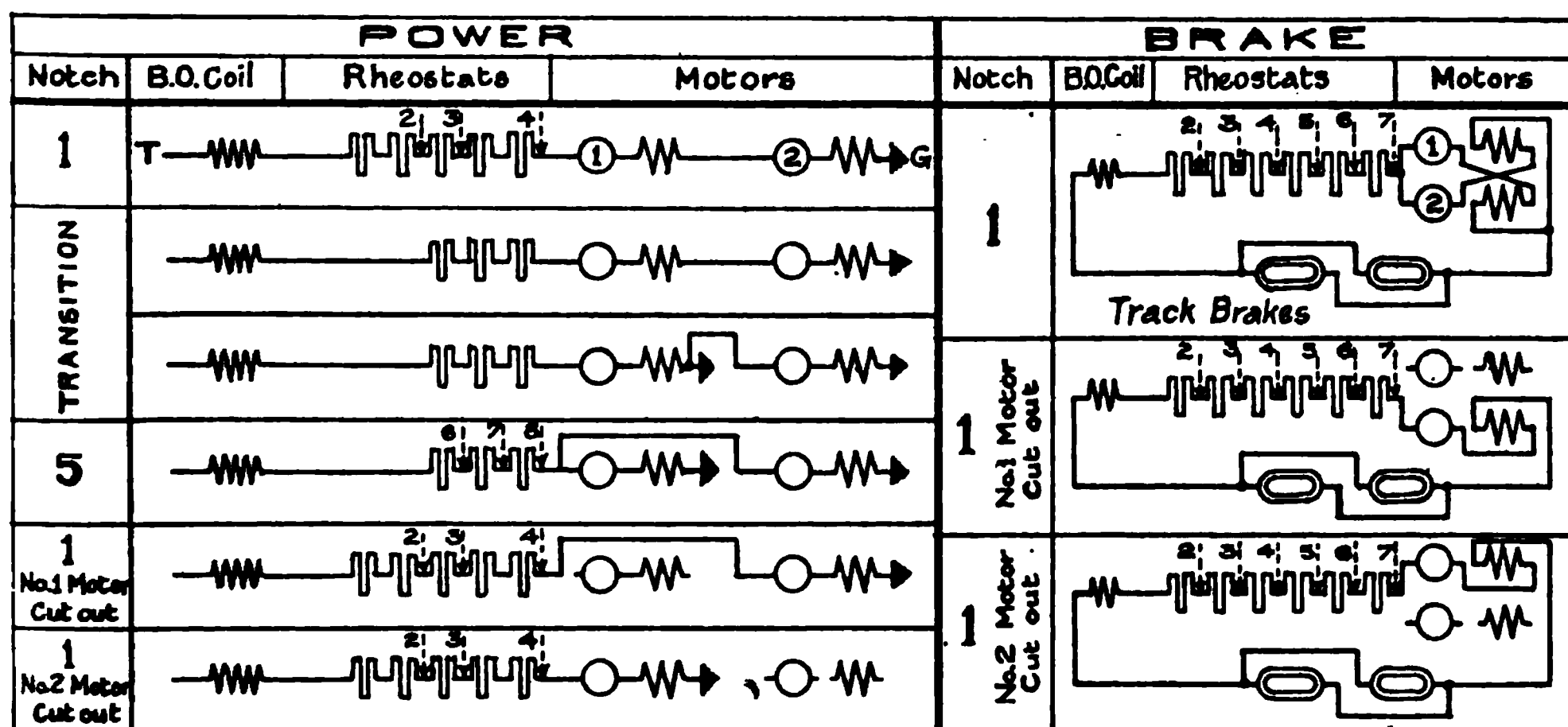


FIG. 129a.—Combinations for B 49 Controller.

cylinder are locked to the reversing spindle and move with it. The movement of the cut-out spindle to cut out a motor, automatically unlocks the corresponding section of the reversing cylinder from its spindle, and locks it in the “ off ” position, so that this section cannot be operated by the reversing spindle. When either motor is cut out, a stop is automatically brought into action, which prevents the main cylinder from being moved beyond the series running notch.

The reversing and cut-out spindles are mechanically interlocked, so that the latter can only be operated when the former is in the “ off ” position. The reversing spindle is also interlocked with the main shaft, so that it cannot be moved unless the latter is in the “ off ” position, and the “ off ” position of the reversing spindle also locks the main shaft in the “ off ” position.

The main shaft is provided with a star-wheel and pawl to give definite notches for the various rheostatic, running, and braking points indicated on the cap-plate. The projecting ends of the spindles are provided

FIG. 130.—B.T.-H. (Type B 18) Controller.

FIG. 131.—British Westinghouse (Type T) Controllers.

with water-caps, and the cover is designed to make a rain-proof fitting on to the back of the controller.

The principal dimensions of the controller are given in Fig. 128.

The development diagram and connections of this controller are shown in Fig. 129, while the combinations are shown in Fig. 129a. From the latter figure it will be observed that the transition from series to parallel is effected by short-circuiting one motor, and that the motors are cross-connected for braking.

Several features of the above controller are common to all tramcar controllers. Thus the interlocking of the cylinders, the method of insulating the cylinders from the shafts, the arrangement of the fingers on finger-boards, the arrangement of the cap-plates, back and cover, differ only in detail among controllers of different manufacturers. In the descriptions of other types of controllers given below we shall, therefore, only refer to their special features.

Fig. 130 illustrates an earlier controller (B 18 type) of the B.T.-H. Co., in which special switches are used for cutting-out a defective motor. These switches are located on the terminal board and are shown in the normal position. To cut-out a motor, one switch is moved to the left-hand contacts, which operation makes suitable connections for cutting-out the motor and, at the same time, operates a cam which provides the series stop on the main cylinder. This controller is provided with four series, three parallel, and six brake notches. One motor is

FIG. 132 — Westinghouse Standard Controller Finger.

FIG. 133.

FIG. 133.—Cross-section of British Westinghouse (Type T) Controller.

short-circuited in transition, and the motors are connected as in Fig. 122a for braking. The development of the reversing cylinder is given in Fig. 120c, while Fig. 121 shows the development of the brake cylinder.

Type T 1 and T 2 Controllers of the British Westinghouse Co.—The special features in these controllers are (1) the arrangement of the reversing cylinder on the same axis as the power cylinder, and (2) the magnetic blow-out. The controllers have four series notches, four parallel notches, and seven brake notches.

Interior views of the T1 and T2 controllers are shown in Fig. 131.

The reversing cylinder is located in the upper portion of the controller, below the cap-plate, and is *concentric* with the main shaft. It is operated by the reversing handle on the right of the main handle.

The main segments occupy the central position of the main shaft, and the brake cylinder is fixed at the lower end.

FIG. 134.—Connections and Development of Westinghouse T 2 Controller.

- * Lift these fingers to cut out motor No. 2.
- † Lift these fingers to cut out motor No. 1.
- ‡ Operating positions for left-hand row of fingers.
- § Operating positions for right-hand row of fingers.

The fingers (see Fig. 132) are provided with renewable tips, and are all fixed to two finger-boards, arranged one on either side of the main cylinder.

The magnetic blow-out is of the "multipolar" type. Two blow-out coils extend the whole length of the main contacts, and are fixed at the extreme sides of the controller back, as shown in the views of Fig. 131 and the cross-sectional drawing of Fig. 133. The coils are connected

so that the projecting pole faces are of opposite polarity. The flux is directed to the main contacts by means of multiple pole-pieces, which also form the deflector plates. Each pole-piece (or deflector plate) consists of an iron plate, of suitable shape, embedded in fireproof com-

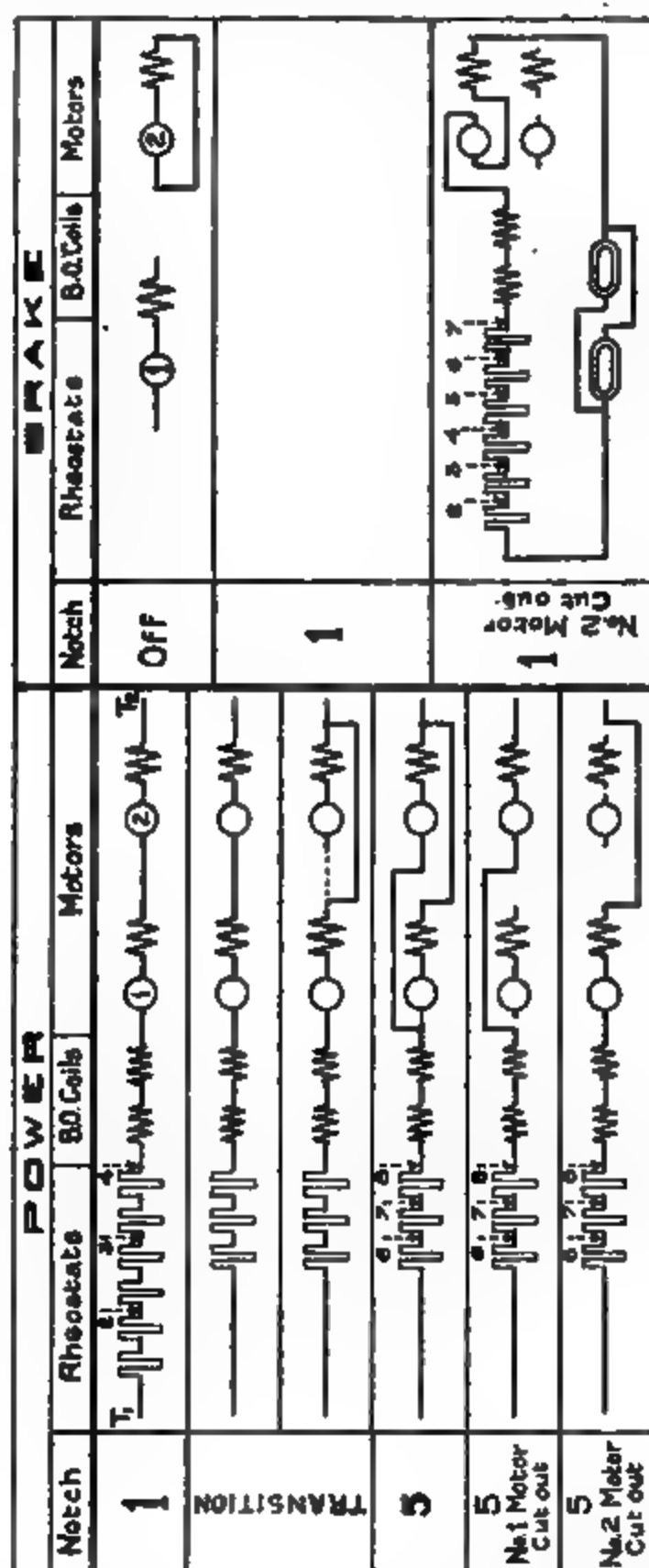


FIG. 134a.—Combinations for T 2 Controller.

pound, the iron extending over about three-quarters of the distance between the pole-faces of the blow-out coils. The plates are bolted together with suitable distance pieces, and are arranged so that the iron portions are alternately in contact with the left and right pole faces. A series of overlapping pole-pieces, alternating in polarity, is therefore

FIG. 135.—Dick-Kerr (Type K) Tramcar Controller.

FIG. 136.—Location of Operating Spindle for Cut-out Device on
Dick-Kerr (Type K) Controller.

obtained in the vicinity of the main contacts; and since the direction of the magnetic field is parallel to the shaft, the arcs between the fingers and segments will be blown outwards (*i.e.* away from the cylinder), and will not impinge on the deflector plates. The deflector plates are slotted, so that any plate can be replaced without dismantling the others, and the frame carrying the deflector plates is arranged on hinges, as shown in Fig. 131.

A defective motor is cut out by raising two fingers—one from the main cylinder and one from the reversing cylinder (see Fig. 134)—these fingers being fitted with catches for holding them out of contact with the cylinders. When a motor is cut-out, power can only be applied to the other motor in the parallel positions of the main cylinder.

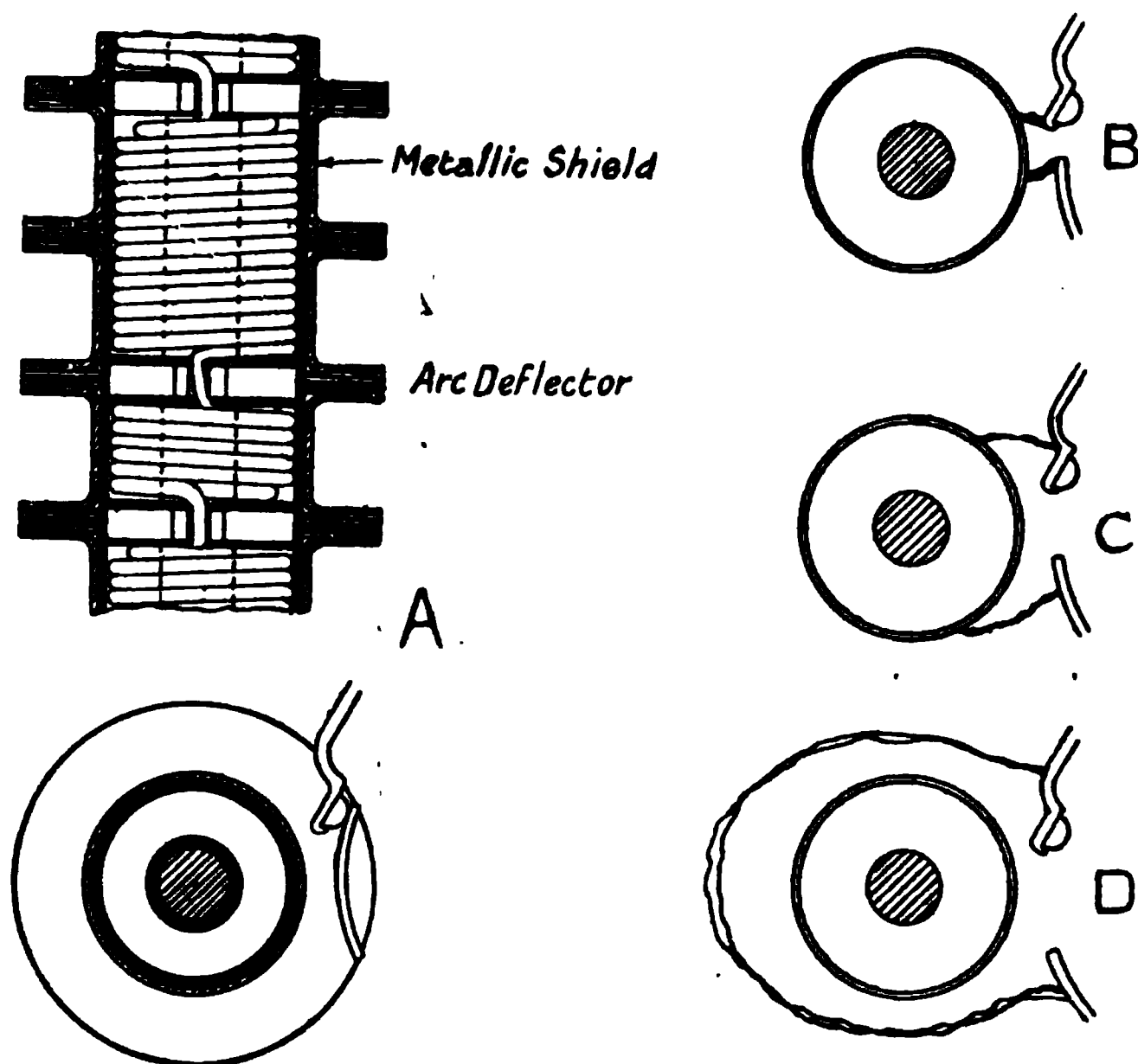


FIG. 137.—Dick-Kerr Metallic-shield Blow-out.

A diagram of the connections and development of the T 2 controller is given in Fig. 134, and the principal combinations are shown in Fig. 134a. This controller is arranged for use on systems having an insulated return (*e.g.* conduit systems), and is extensively adopted on the London County Council tramways.

Type K Controller of Messrs. Dick, Kerr & Co.—This controller possesses several features in common with the controllers already described, such as a mica-insulated square shaft carrying the main segments and brake cylinder, externally operated cut-out switches, fingers and segments with renewable tips, and the same number of notches (*i.e.* four series, four parallel, and seven brake).

The controller differs from the above types in two important features, *viz.* (1) the novel form of magnetic blow-out, and (2) the mechanical device which prevents the main handle being moved forward more than

one notch at a time. This device is only operative on the power notches when the handle is being moved *from* the "off" position. The movement of the handle from any power position *to* the "off" position is unrestricted, while the motion to or from the brake notches is also unrestricted.

Interior views of this controller are shown in Fig. 135, and Fig. 136 is a view showing the position of the cut-out switch on the back of the controller.

The **cut-out switch** is operated by the reversing handle, and consists of a mechanical device for raising or lowering the reversing cylinder (in the "off" position of the latter) so that the relative positions of the fingers and segments are changed. By arranging the fingers and segments of this cylinder in a certain order, the cutting-out of either motor can be accomplished by raising or lowering the cylinder, from the central position, through a distance corresponding to the pitch of the fingers.

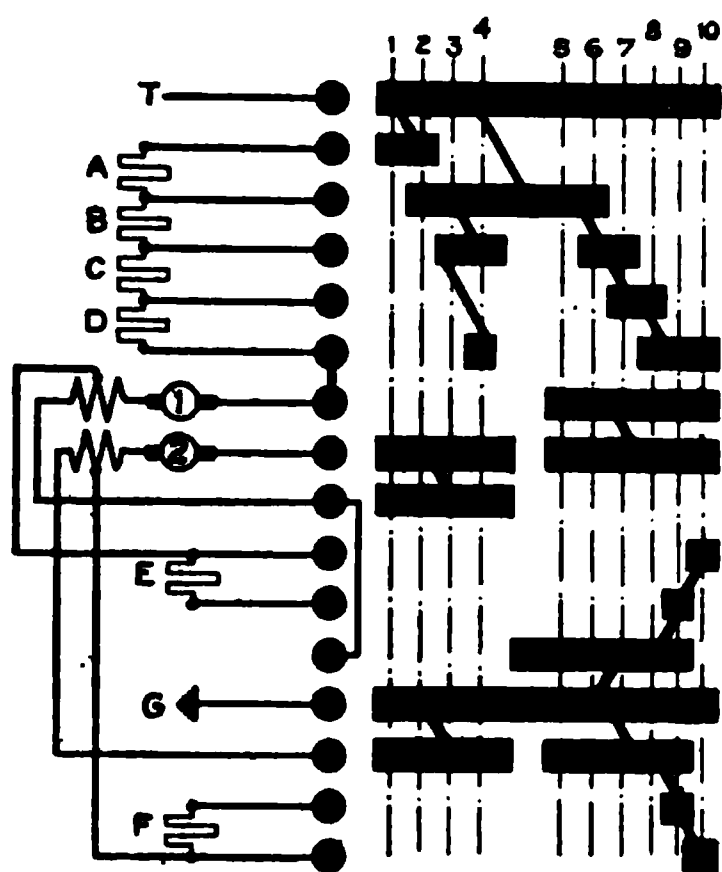


FIG. 138a.

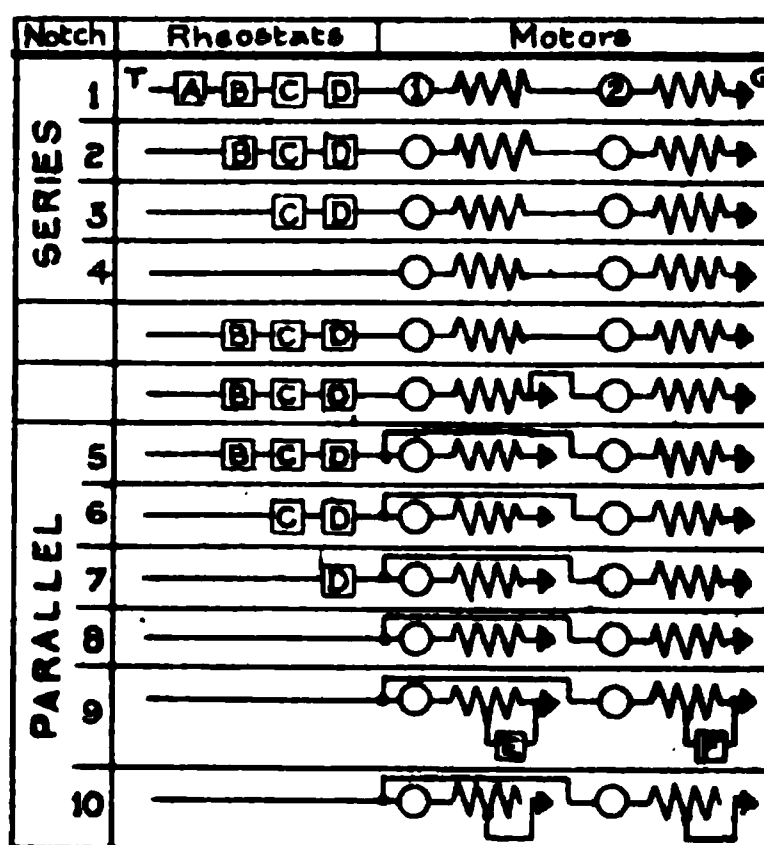


FIG. 138b.

Connections, Development, and Combinations of Series-parallel Controller arranged for field control in parallel notches.

Thus, when the reversing cylinder is in the central (or normal) position, both motors are in circuit; when the cylinder is raised, one motor (No. 1) is cut out; while, when the cylinder is lowered, the other motor (No. 2) is cut out.

The **magnetic blow-out** is of the solenoid "metallic-shield" type, and is illustrated in detail in Fig. 137. Essentially the blow-out consists of an iron core on which is wound a solenoid, the direction of the winding being arranged to give a number of consequent poles along the core. The poles are arranged with reference to the positions of the main contacts (and also to the direction of the current), so that the contacts at which large currents have to be broken are situated in a strong magnetic field. The outside of the solenoid is sheathed with thin copper, and is fitted with a number of arc deflectors, the purpose of which is to prevent short-circuits being formed between adjacent arcs. The "metallic shield" is located close to the main contacts (see Fig. 137, A) so that the arc is drawn outwards until it strikes the shield, this stage being represented at B (Fig. 137). It will be observed that the path of the current

is now from the finger to the shield and from the shield to the segment, consequently the arcs will be blown farther apart as represented at *C*, and will finally unite again, as represented at *D*, if the voltage is high enough. In practice the arcs are ruptured before reaching this stage. The blow-out action occurs very rapidly, and the metal of the shield is unaffected by the action of the arc.

The solenoid is short-circuited on the series and parallel running notches, and is connected to the controller wiring by switch contacts, so that the blow-out shield may be readily swung clear of the main contacts or removed from the controller.

CONTROLLERS FOR TAP-FIELD CONTROL

Although field control equipments are not yet adopted extensively, it will be of interest to discuss the requirements in controllers for these

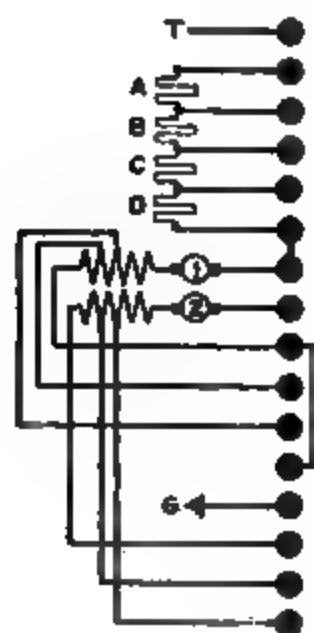


FIG. 139a.

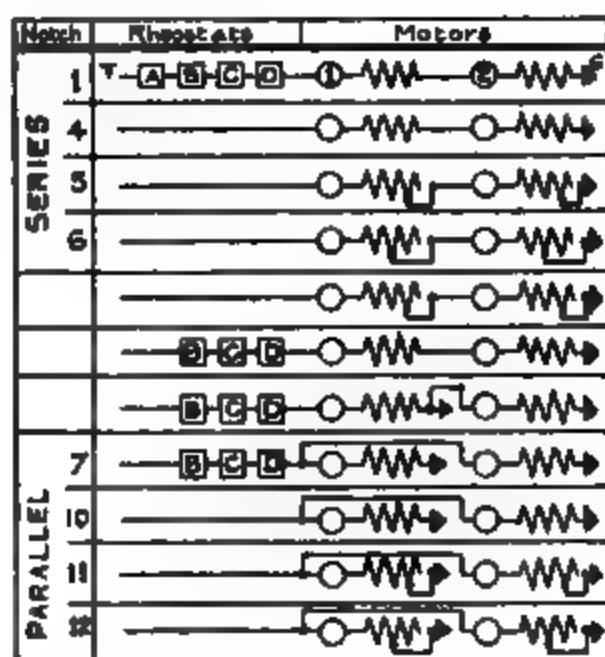


FIG. 139b.

Connections, Development, and Combinations of Series-parallel Controller arranged for field control in series and parallel notches.

equipments. In this method of control, as applied to electric traction, the motors are operated with weakened fields in the running positions of the controller, and in consequence a greater number of running speeds are obtained.

Thus, if the field windings of the motors are provided with one tapping—arranged to give, say, $\frac{2}{3}$ of the "full" field—then four running speeds are available, viz. two speeds with the motors in series, and two speeds with the motors in parallel, the two speeds in the series or parallel combinations of the motors corresponding to "full field" and "tap field." Again, if two tapplings are provided, six speeds can be obtained.

A slight modification of this method of control was adopted in the early days (about 1898) of electric traction, but was abandoned on account of the unsatisfactory performance of the motors with weakened fields.*

* The method consisted of connecting a rheostat in parallel with the field winding on the series and parallel running notches. The controllers developed by the General Electric Co. (of Schenectady) for this method of control were designated Type K 2.

The introduction of commutating poles, however, has enabled these difficulties to be overcome, and modern commutating-pole motors may be operated satisfactorily on a 50 per cent. field tapping.

Field-control equipments possess several advantages over ordinary equipments, especially where the cars have to operate in congested city traffic and on outlying routes. The low speeds incidental to city traffic may be obtained economically by operating the motors with full field, and the higher speeds required for the outlying districts can be obtained by operating the motors with weakened fields. These features, and their effect on the energy consumption, are discussed in greater detail in Chapter XIX. For the present we have to consider how the additional speeds affect the design of the controller.

The simplest case occurs when the weakened fields are only used with the motors operating in parallel. In this case the series, transition, and rheostatic-parallel points of the controller are the same as those for a standard series-parallel controller. The transition from full field to tap field is effected by short-circuiting a portion of the field winding and then cutting this portion out of circuit; but if the change is effected in one operation, the motor may be subjected to a large rush of current. The magnitude of this rush of current will depend on the portion of the motor speed-curve at which the change from full field to tap field is made, as well as on the relative field turns in circuit. For instance, with the motor to which the characteristic curves of Fig. 31 (p. 48) refer, if the transition from full field to normal field (*i.e.* $\frac{2}{3}$ full field) be effected in one operation when the speed is 17 ml.p.h., the current will increase suddenly from 130 amperes to 188 amperes. Although this rush of current may not be objectionable for this particular motor, it is apparent that if the change were made from full field to the minimum field (*i.e.* 50 per cent. of full field) in one step, the rush of current would be excessive. If, however, the change were made at a higher speed—say, 25 ml.p.h.—then the rush of current would not be objectionable as far as the operation of the motor was concerned.

The magnitude of the rush of current may be reduced by introducing an intermediate step in the transition from full field to tap field. Thus, instead of directly short-circuiting a portion of the field winding, a rheostat is connected in parallel with this portion of the winding, and the rheostat, together with the portion of the winding, is finally cut out of circuit. The connections, combinations, and development of a controller for this method of control are shown in Fig. 138. It will be observed that the transition from series to parallel is effected, with full field, by short-circuiting one motor.

In cases where the tap field is required to be used for series running, it is necessary to change to full field before passing into the parallel notches, in order that the rheostatic acceleration on these notches may take place efficiently. The connections, combinations, and development of a controller for performing these functions are shown in Fig. 139. The transition from series to parallel is effected, with full field, by short-circuiting one motor, and six running speeds are provided.

Controllers for field control are now manufactured by the principal manufacturers of traction equipment, and it is probable that in future tramway installations these controllers will be adopted in conjunction with "tap-field" motors. It may be remarked that this method of control has been adopted in several recent railway electrifications abroad.

CHAPTER IX

THE CONTROL OF CONTINUOUS-CURRENT RAILWAY MOTORS

ELECTRIC trains for suburban service are usually made up of a number of motor and trail coaches, and the composition of the train is altered to suit the traffic. Thus for light traffic one motor-coach and one trailer may be sufficient, while for heavy traffic two or more motor-coaches and a number of trailers may be required. Each motor-coach may be equipped with two or four motors, but all of the motors throughout the train must be controlled simultaneously from one point.

Where two motor-coaches are used, the control may be carried out in a manner similar to that adopted on tramcars by arranging the motor-coaches at the ends of the train and equipping each with a controller capable of controlling all the motors. With this type of control (known in electric railway work as the "**direct control**" system) the whole of the power must pass through the controller at the driving end of the train, and it is necessary to have cables from end to end to interconnect the controllers on each motor-coach. If the reversing is done at the controller, the number of train cables will be large, even if only two motors are used on each motor-coach, and the majority of these cables must be of heavy cross-section. If a remote controlled electrically operated reversing switch is used for each motor, then the heavy train cables may be reduced to a minimum of four, but to obtain this result it is necessary to duplicate the starting rheostats on each motor-coach, only one set—that on the leading coach—being in use at once.

This system of control is in service on the **Liverpool-Southport** section of the Lancashire and Yorkshire Railway, the trains being made up of one or two motor-coaches and a number of trailers. Each motor-coach is equipped with four 150-H.P. 600-volt motors,* a series-parallel controller—which is capable of controlling two motor-coaches—and the necessary rheostats. Of the four motors on each motor-coach, two are connected permanently in parallel, and the two pairs are controlled on the series-parallel system.

The controller is illustrated in Fig. 140. The two main cylinders are geared together and are operated by one handle. Each cylinder controls the four motors on one motor-coach, so that the controller is capable of handling a train equipment of 1800 H.P. The cylinders are

* The whole of the train equipments are of Messrs. Dick, Kerr & Co.'s manufacture. It is interesting to note that these equipments were the first in operation on a main-line railway in this country.

each provided with a magnetic blow-out of the metallic-shield type (see Chapter VIII, p. 161).

An inspection of the connection and development diagram in Fig. 141 will show that there are five series notches and three parallel notches.

These controllers are probably the largest of their class in operation, and, considering the large amount of power handled, the overall dimensions are relatively small, the approximate dimensions being: width, 2 ft. 3 in.; depth, 1 ft. 2 in.; height, 3 ft. 10 in.

The reversing of the motors is accomplished by means of manually-operated reversing switches, of which one is provided for each motor-coach and is located in the driving compartment. These reversing switches are of the drum type, and have only "forward" and "reverse" positions. Only one handle is provided for the two reversers on a train, and the handle can only be removed when the reverser on the driving coach is thrown to the "reverse" position. Thus, when the motorman goes to the other end of the train and throws the reverser there to the "forward" position, the motors on both motor-coaches will be connected in the correct manner.

In the event of the train requiring to be reversed (for, say, shunting purposes) from the driving coach, the circuit-breaker in circuit with the motors on the rear coach would be tripped. (NOTE.—The circuit-breakers for both coaches are located in the driving compartments and are duplicated in the same manner as the controllers.)

In order to prevent power from being applied from both front and rear controllers at the same time,

FIG. 140a.—Dick-Kerr (Type DM 4) Controller.

each controller is fitted with a small auxiliary cylinder which is provided with a removable handle and is interlocked with the main cylinder, so that the latter cannot be operated when the handle on the auxiliary cylinder is removed. The auxiliary cylinder also controls the "no-voltage" release coils of the circuit-breakers, so that power cannot be obtained on the main cylinders of the controller until the auxiliary cylinder has been thrown "on." Thus, as far as interlocking is concerned, the auxiliary cylinder acts in the same manner as the reversing cylinder on a tramcar controller.

A reference to Fig. 141 will show that the auxiliary cylinder is pro-

vided with three sets of main segments and fingers, the function of which is to connect *B* and *BB*, *C* and *DD*, *D* and *CC* when this cylinder is in the "off" position, and to open these connections when this cylinder is moved to the "on" position. Thus the two groups of motors on the rear motor-coach are interconnected through No. 2 controller, and can therefore be controlled from the driving (No. 1) controller, since the

FIG. 140b.—Dick-Kerr (Type DM 4) Controller. (Blow-out shields opened.)

interconnections at this controller are opened. When the train is to be driven from No. 2 controller, the auxiliary cylinder on No. 1 controller is moved to the "off" position (which interconnects the motors on that coach), and the auxiliary cylinder on No. 2 controller is moved to the "on" position, which opens up the motor connections and enables the control to be performed from the main cylinders of No. 2 controller.

The principal power connections for a single motor-coach are shown in Fig. 141, in which are also shown the "jumper" cables and the "train

each provided with a magnetic blow-out of the metallic-shield type (see Chapter VIII, p. 161).

An inspection of the connection and development diagram in Fig. 141 will show that there are five series notches and three parallel notches.

These controllers are probably the largest of their class in operation, and, considering the large amount of power handled, the overall dimensions are relatively small, the approximate dimensions being: width, 2 ft. 3 in.; depth, 1 ft. 2 in.; height, 3 ft. 10 in.

The reversing of the motors is accomplished by means of manually-operated reversing switches, of which one is provided for each motor-coach and is located in the driving compartment. These reversing switches are of the drum type, and have only "forward" and "reverse" positions. Only one handle is provided for the two reversers on a train, and the handle can only be removed when the reverser on the driving coach is thrown to the "reverse" position. Thus, when the motorman goes to the other end of the train and throws the reverser there to the "forward" position, the motors on both motor-coaches will be connected in the correct manner.

In the event of the train requiring to be reversed (for, say, shunting purposes) from the driving coach, the circuit-breaker in circuit with the motors on the rear coach would be tripped. (NOTE.—The circuit-breakers for both coaches are located in the driving compartments and are duplicated in the same manner as the controllers.)

FIG. 140a.—Dick-Kerr (Type DM 4) Controller.

In order to prevent power from being applied from both front and rear controllers at the same time, each controller is fitted with a small auxiliary cylinder which is provided with a removable handle and is interlocked with the main cylinder, so that the latter cannot be operated when the handle on the auxiliary cylinder is removed. The auxiliary cylinder also controls the "no-voltage" release coils of the circuit-breakers, so that power cannot be obtained on the main cylinders of the controller until the auxiliary cylinder has been thrown "on." Thus, as far as interlocking is concerned, the auxiliary cylinder acts in the same manner as the reversing cylinder on a tramcar controller.

A reference to Fig. 141 will show that the auxiliary cylinder is pro-

vided with three sets of main segments and fingers, the function of which is to connect *B* and *BB*, *C* and *DD*, *D* and *CC* when this cylinder is in the "off" position, and to open these connections when this cylinder is moved to the "on" position. Thus the two groups of motors on the rear motor-coach are interconnected through No. 2 controller, and can therefore be controlled from the driving (No. 1) controller, since the

FIG. 140b.—Dick-Kerr (Type DM 4) Controller. (Blow-out shields opened.)

interconnections at this controller are opened. When the train is to be driven from No. 2 controller, the auxiliary cylinder on No. 1 controller is moved to the "off" position (which interconnects the motors on that coach), and the auxiliary cylinder on No. 2 controller is moved to the "on" position, which opens up the motor connections and enables the control to be performed from the main cylinders of No. 2 controller.

The principal power connections for a single motor-coach are shown in Fig. 141, in which are also shown the "jumper" cables and the "train

4

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FIG. 141.—Connections for Dick-Kerr system of "Direct" Control
as applied to Motor-coach Trains.

line" cables, by means of which the front and rear motor-coaches are electrically connected together. The duplication of the "T" and "BB" cables is required on account of the possibility of the trailer coaches being changed round when uncoupled from the motor-coaches.

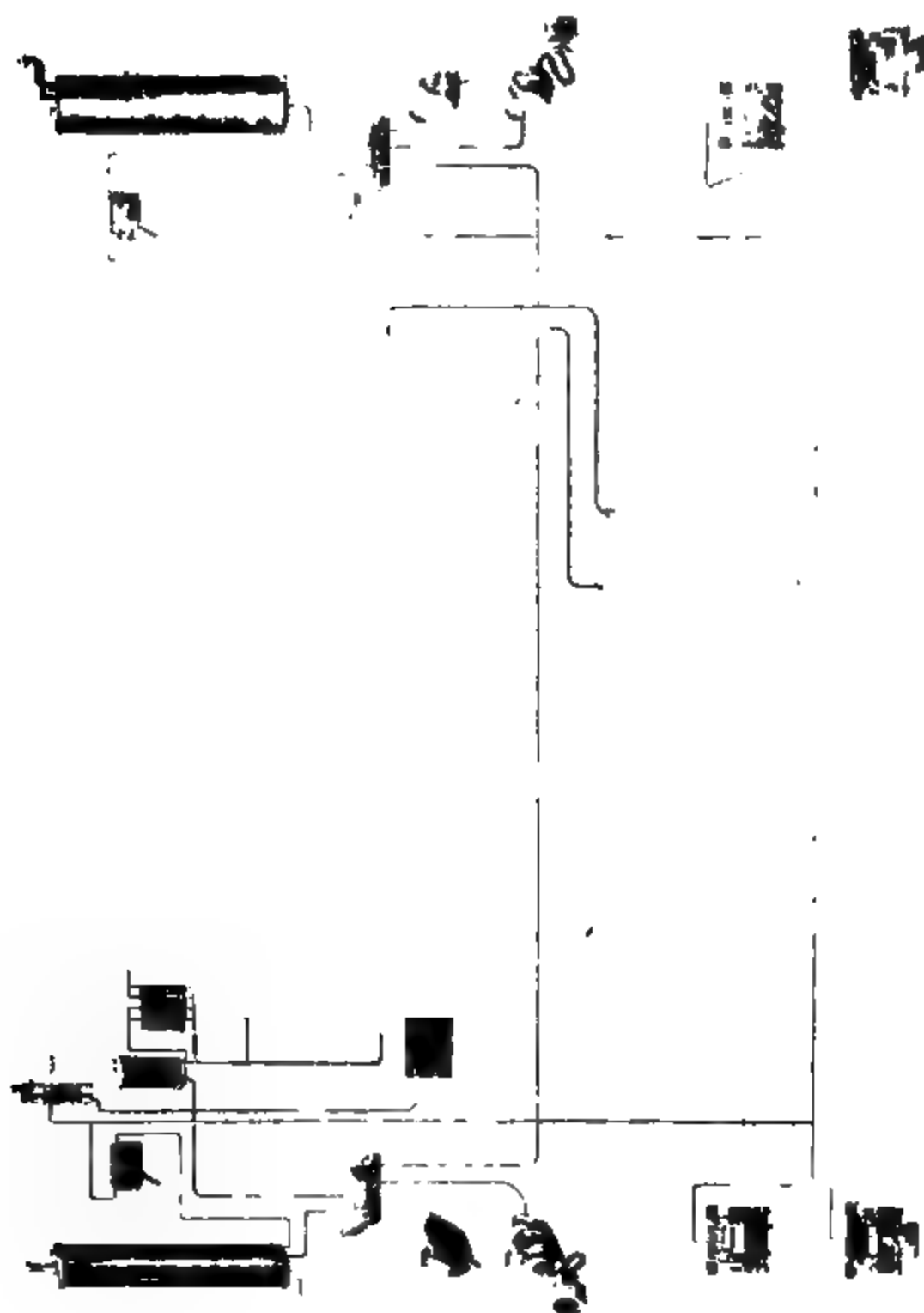


FIG. 142.—Apparatus forming one "Unit" of B.T.H. (Type M) Multiple-unit Control System.

The above system of control, while giving a certain degree of flexibility to the composition of the train, limits the heaviest train to that which can be handled by two motor-coaches. In order to obtain greater flexibility, an indirect method of control—known as the **multiple-unit system**—has been developed. In this system each group of two or four motors is provided with a series-parallel controller, a reverser, starting

rheostats, and current-collecting gear, and is considered as *one unit* of the train equipment. The motor-controller and reverser of each unit are electrically operated and remote controlled from a master controller, which supplies current to the control circuit of the motor-controller. The simultaneous control of any number of motor-controllers is obtained by connecting their control circuits in parallel. The motor circuits are quite separate from the control circuit, and are not interconnected, except by the current-collecting gear.

Master controllers may be located at different parts of the train, and all master controllers are connected in parallel, so that the whole train equipment may be operated from any master controller. The

current for operating all the control circuits passes through the master controller at the driving end of the train, and is conducted to the various motor-controllers by a multiple-conductor cable.

With this system of control we obtain the maximum flexibility in the composition of the train, since, as far as the control is concerned, the maximum number of motor-coaches is only limited by the current-carrying capacity of the master controller and the control-circuit cable. Usually, however, the length and weight of the train are the limiting conditions. A further advantage is that the master

FIG. 143.—B.T.-H. (Type 1D) 2-60) Contactor

controllers occupy very little cab space, and the motor-controllers may be located underneath the coaches.

The multiple-unit system of train control has received its greatest development in the United States of America from the General Electric Co. (Schenectady) and Westinghouse Co. In that country the system is used on an extensive scale, and, in fact, has entirely superseded large controllers.

In the system developed by the General Electric Co. (and also by the British Thomson-Houston Co.) the electro-magnetic, or "all electric" principle has been adopted; while in the Westinghouse Co.'s system (usually known as "unit switch control") both the "all electric" and the "electro-pneumatic" principles are used. The "all electric" principle is also used in the systems developed by Messrs. Dick, Kerr & Co., by Messrs. Siemens, and by the Oerlikon Co. We will now consider some of these systems in detail.

The General Electric and British Thomson-Houston Multiple-

unit System (known as Type M control).^{*} The apparatus comprising one unit of the train equipment is illustrated in Fig. 142. The **motor-controller** consists of (1) a number of electrically-operated switches or "contactors," by means of which the combinations of the motors and rheostats are effected; (2) an electrically-operated reversing switch or "reverser"; and (3) the necessary rheostats.

Each **contactor** consists essentially of (a) two contacts or fingers, one being fixed and the other movable; (b) a magnetic blow-out; and (c) a plunger-type electromagnet. An illustration of a modern contactor is shown in Fig. 143. The plunger *P* operates two arms *A*, *B*, of which

FIG. 144.—B.T.-H. Contactor Box.

the arm *A* is hinged to the frame and plunger at *C* and *D* respectively, while the arm *B*, which carries the moving contact, is hinged to the arm *A* at *E*, the relative positions of the arms being maintained by the springs *S*. The **moving contact** is, therefore, in connection with the frame of the contactor, and, to avoid the passage of the current through the pin joints, flexible copper shunts *F* connect the contact directly to the frame. This contact operates in an arc-chute *G* of fireproof material in which the fixed contact is located, the latter being arranged vertically above the moving contact. The **fixed contact** is connected, through a blow-out coil (located in the upper portion of the arc-chute), to the ter-

^{*} This system of control is in service on practically all the London Electric Railways (with the exception of the London and South-Western and the London and North-Western Railways); it is also in service on the North-Eastern Railway. Recently the British Thomson-Houston Co. have supplied equipments for the Victorian Railways (Australia) and the Central Argentine Railway.

minal *T*, the other terminal of the contactor being fixed to the frame. The magnetic circuit of the **blow-out coil** is formed by an iron core and two sheet-iron pole pieces, one of which is shown at *H*. The pole-pieces are designed to produce a strong magnetic field in the vicinity of the main contacts, and the latter are fitted with curved horns to provide a definite path for the arc. In this manner the arc is confined to the centre of the arc-chute, and heavy currents may be broken successfully without burning the main contacts.

An important feature in the operation of the contactor is the rolling or "**wiping**" action which takes place at the contacts when the con-

FIG. 145.—B.T.-H. (Type DB 26) Reverser.

tactor closes. This action is brought about by the springs *S* as follows: When the plunger is lifted, the arms *A*, *B* move together as a single arm about the fulcrum *C* until the contact tips touch. The vertical motion of the outer end of the contact-arm *B* is then arrested, and, since the plunger has not completed its stroke, further vertical motion of *B* can only take place at the hinge *E*. The flexible link formed by the springs *S* allows this motion to occur at *E*, and, at the same time, the moving contact rolls on the fixed contact, so that the main portions of the contacts are brought together. In opening, the reverse action takes place, so that arcing can only occur at the contact tips. The springs also provide the necessary pressure between the contacts to enable them to carry the current without overheating. Moreover, the springs force the

contact arm to move rapidly when the circuit of the operating coil is interrupted.

The operating coil *J* is wound in two sections. The number of turns on the coil are sufficient to ensure satisfactory operation of the contactor at one-half of the normal operating voltage. The normal operating current is about 1 ampere.

In order to prevent incorrect operation of the contactors the operat-

FIG. 146.

FIG. 147.

Master Controllers for B.T.-H. Multiple-unit Control System. (Fig. 146, Type C 28 Controller for Non-automatic Control; Fig. 147, Type C 35 Controller for Automatic Control.)

ing coils are electrically interlocked by means of auxiliary contacts controlled by the plunger. The auxiliary contacts are fixed to the back of the contactor frame, and the circuit between these contacts is opened or closed by means of a short-circuiting bridge, the motion of which is dependent on the motion of the plunger. For example, the lower end of the rod *K* (Fig. 143) —to which the short-circuiting bridge is fixed —carries an insulating block *L*. A pin in this block is connected to one end of a bell-crank lever *M*, which is pivoted to the frame at *N*, and the other end of this lever is connected to the plunger by the pin *D*.

The auxiliary contacts and short-circuiting bridges can be seen in the view of the reverser (Fig. 145). It should be remarked that some of the auxiliary contacts are provided with small blow-out coils, *O* (see also connection diagram, Fig. 151).

A number of contactors, from 12 to 16, depending on the method of control, are assembled in a box with a removable cover, the box being generally located under the car. Views of a typical contactor box are shown in Fig. 144. All the small wiring between the contactors is brought to a terminal board from which connections are made to the conductors of the multiple-conductor control cable.

The reverser (Fig. 145) is also electrically operated. The armature and field circuits of each pair of motors are connected to two groups of fingers—of which one group is visible in Fig. 145—and these fingers may be interconnected by two sets of segments in a manner similar to that adopted for the reversing cylinder of a tramcar controller. The

FIG. 148.—Control-circuit Coupler Plug and Socket (B.T.-H. Co.).

segments are mounted on an insulating cylinder which can be moved to the two positions (viz. "forward" and "reverse") by two plunger-type electro-magnets, one magnet being provided for each position of the cylinder. The solenoids are energised from the master controller, and the plungers also operate auxiliary contacts, by means of which the reverser is electrically interlocked with the control circuit of the contactors, so that the latter cannot be operated unless the reverser is in the correct position.

Two types of **master controllers** have been developed. In one type (Fig. 146) the operation of the contactors is under the control of the driver, and the controller has to be "notched-up" in the same manner as a tramcar controller. In the other type (Fig. 147) the operation of the contactors is automatic, and the controller handle has only certain operating positions. Of the two types, the former (or non-automatic) type has been largely adopted in this country, but in recent electrifications the automatic type has been adopted, since, with this type of controller, the accelerating current of the motors can be maintained constant at a predetermined average value.

We will first discuss the **non-automatic controller** (Fig. 146). This controller has separate handles for operating the main and reverse

cylinders, the handle for the former being non-removable and provided with an automatic feature, which gives it the name of the "dead-man's handle." The main cylinder *A* is operated through gearing from the shaft *S* carrying the main handle, so that a 180-degree movement of the latter corresponds to nearly a full revolution of the main cylinder. By this arrangement it is possible to mount the controller directly against the vestibule of the coach. The fingers *B*, corresponding to the main cylinder, are connected to the operating coils of the contactors in the manner shown in Figs. 149, 150. These fingers are provided with a

Reverser

I

FIG. 149.—Simplified Connections for Type M Multiple-unit Control using Open-circuit Transition. NOTE.—The control-circuit cable and coupler sockets are omitted. The interlocks open when the contactors close.

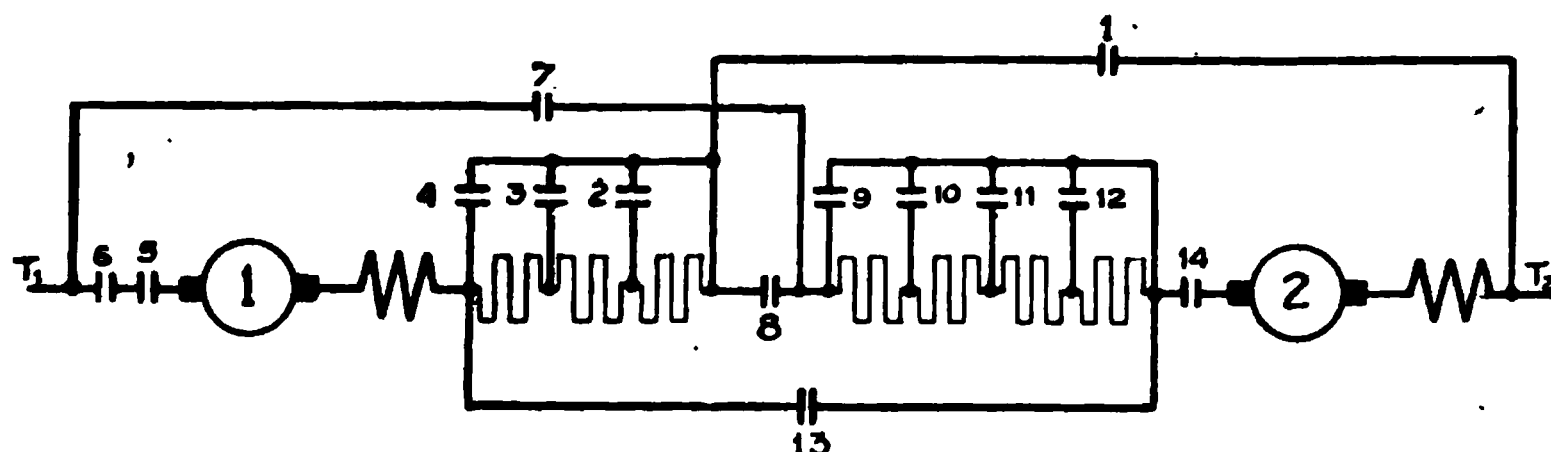
magnetic blow-out of the "shaft" type, the blow-out coil being shown at *C*. The arc deflectors *D* are mounted on a hinged pole-piece *E*, which fits against a projection *F*, forming part of the controller base.

A pair of contacts *J*—located in a chamber of fireproof insulation and provided with a blow-out coil *H*—are attached to the controller-back just above the main cylinder. These contacts are connected in series with the control circuit, and can be bridged by two fingers *G*, which are carried on a block of insulating material fixed to a lever *K*. This lever is operated by a spring *L*, which can be connected to the shaft *S* by depressing the button *M* on the main handle when the latter is in the "off" position. The movement of the handle (with the button

FIG. 150.—Connections for B.T.-H. (Type M) Control System using Bridge Transition. *NOTE.*—The interlocks are shown in the “open” position of the contactors. When the contactors close, the short-circuiting bridges of the interlocks move downwards.

depressed) then causes the fingers *G* to close, thereby completing the control circuit to the main cylinder. If the button is released on any notch, except the "off" position, the spring *L* will cause these fingers to open, thereby automatically interrupting the control circuit. It is customary to arrange for an emergency valve—connected to the train-pipe of the air-brake—to open at the same time as the control circuit is opened, thereby producing an application of the brakes in addition to cutting-off power from the train. It is necessary, therefore, for the motorman to keep the button depressed the whole time that power is supplied to the motors.

The reversing cylinder *N* is really a two-way switch, by means of



Notch	Contactors													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SERIES	1				●	●		●						●
	2				●	●		●				●		●
	3		●		●	●		●			●	●		●
	4		●	●	●	●		●		●	●	●		●
	5		●	●	●	●		●	●	●	●	●		●
PARALLEL	6	●			●	●	●					●		●
	7	●	●		●	●	●				●	●		●
	8	●	●	●	●	●	●			●	●	●		●
	9	●	●	●	●	●	●		●	●	●	●		●
	10				●	●							●	●

FIG. 150a.—Motor-circuit Connections and Order of Closing of Contactors for Fig. 150.

which either the one or the other of the solenoids on the reversers may be operated.

The master controller for automatic control (Fig. 147) is considerably simpler than the non-automatic controller described above. The controller is provided with only one handle which is non-removable, and is operated in one direction for "forward" and the other direction for "reverse." The cylinder moves against the pressure of a spring, and is thrown immediately to the "off" position if the handle is released. Four notches (viz. two series and two parallel) are provided in the "forward" position, and two (series) notches in the "reverse" position. The two notches are required for series and parallel so that the automatic operation of the contactors may be arrested at any point in the starting period without returning the handle to the "off" position. (The manner in which this is accomplished is considered below.)

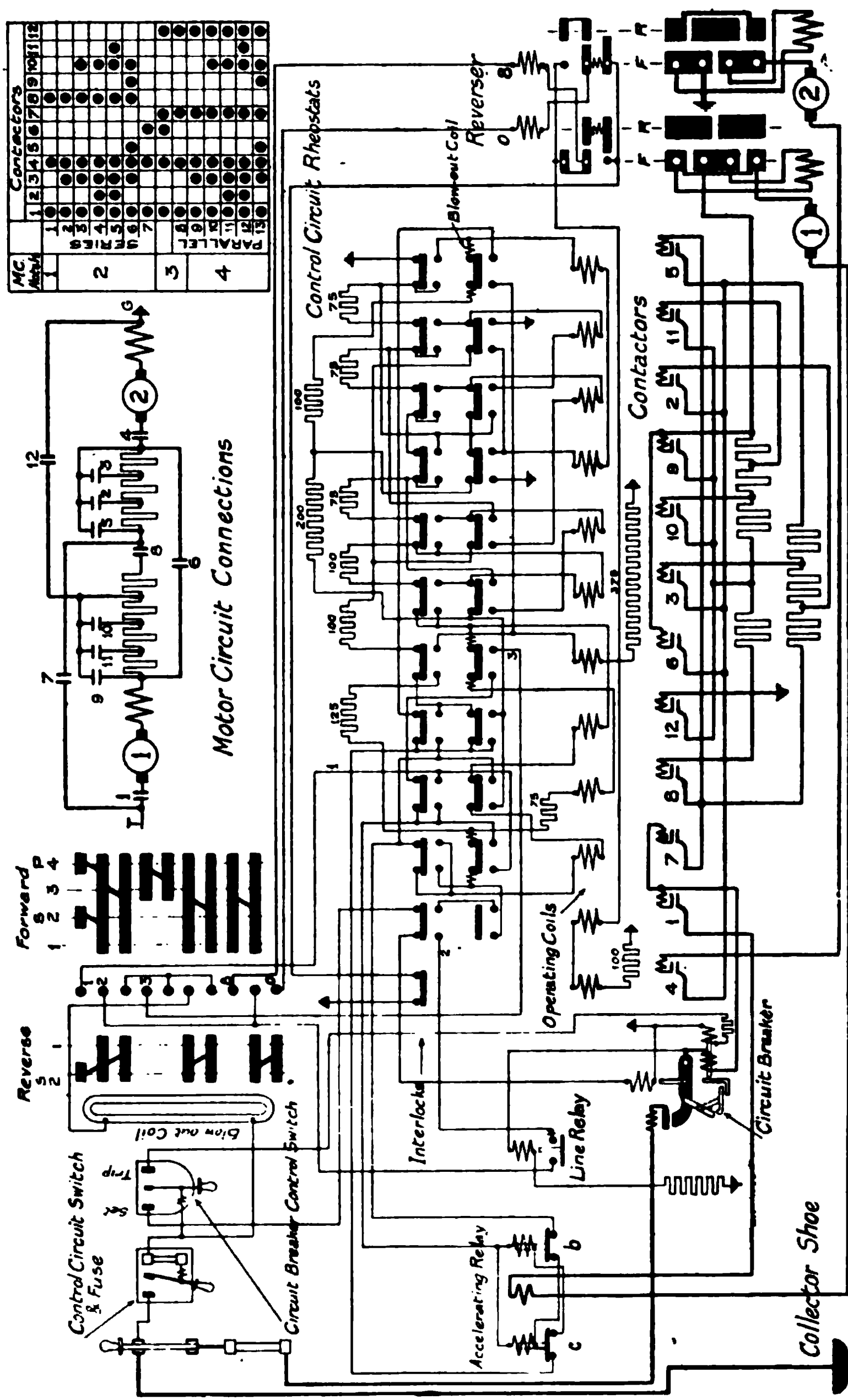


FIG. 151.—Connections for Sprague B.T.-H. Automatic Control System. NOTE.—The interlocks are shown in the “open” position of the contactors. When contactors close, the short-circuiting bridges of interlocks move downwards. The numbers against the control-circuit rheostats refer to their resistances (ohms). The coupler sockets, connection boxes, and cut-out switches are not shown.

TABLE SHOWING PATHS OF CONTROL CIRCUITS FOR FIG. 151.

Master Controller Notch.	Step.	"Actuating" Circuit.	"Retaining" Circuit.	"Rever- ser" Circuit.
1	1		II— $LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_1-100-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G$.	VIII— $Rc-Ri-1c-4c-100-G$.
2	2	I— $8i_2-AR_b-8i_4-3i_3-3c-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G$.	II— $LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_2-3c-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G$.	" "
2	3	I— $8i_2-AR_c-12i_3-6i_1-100-10i_3-10c-3i_4-9i_1-2i_1-75-11i_1-75-5i_1-G$.	II— $LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_1-75-11i_1-75-5i_1-G$.	" "
2	4	I— $8i_2-AR_b-8i_4-200-9i_3-2i_3-2c-10i_4-11i_1-75-5i_1-G$.	II— $LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_2-2c-10i_4-11i_1-75-5i_1-G$.	" "
2	5	I— $8i_2-AR_c-12i_3-6i_1-100-11i_3-11c-2i_4-5i_1-G$.	II— $LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_2-2c-10i_4-11i_2-11c-2i_4-5i_1-G$.	" "
2	6	I— $8i_2-AR_b-8i_4-200-100-5i_3-5c-9c-11i_4-G$.	II— $LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_2-3c-10i_2-10c-3i_4-9i_2-5i_2-5c-9c-9i_4-G$.	" "
2	7	I— $8i_2-AR_c-12i_1-5i_4-6c-375-G$.	II— $LR-1i_2-1i_4-7i_3-125-6i_2-6c-375-G$.	" "
3	Tr. & 8	III— $6i_4-8i_1-AR_b-7i_1-7c-8i_3-12c-3i_1-100-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G$.	II— $LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_1-100-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G$.	" "
4	9	I— $7i_4-AR_c-12i_4-3i_3-3c-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G$.	II— $LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_2-3c-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G$.	" "
4	10	I— $7i_4-AR_b-12i_2-6i_1-100-10i_3-10c-3i_4-9i_1-2i_1-75-11i_1-75-5i_1-G$.	II— $LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_1-75-11i_1-75-5i_1-G$.	" "
4	11	I— $7i_4-AR_c-12i_4-200-9i_3-2i_3-2c-10i_4-11i_1-75-5i_1-G$.	II— $LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_2-2c-10i_4-11i_1-75-5i_1-G$.	" "
4	12	I— $7i_4-AR_b-12i_2-6i_1-100-11i_3-11c-2i_4-5i_1-G$.	II— $LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_2-2c-10i_4-11i_2-11c-2i_4-5i_1-G$.	" "
4	13	I— $7i_4-AR_c-12i_4-200-100-5i_3-5c-9c-11i_4-G$.	II— $LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_2-3c-10i_2-10c-3i_4-9i_2-5i_2-5c-9c-9i_4-G$.	" "

NOTE.—Roman numerals I, II, III, VIII denote fingers on master controller; Arabic numerals 1-12 denote contactors, 75-375 denote resistances (ohms) of control-circuit rheostats; AR_b , AR_c denote contacts of accelerating relay; LR denotes contacts of line relay; R denotes reverser; c denotes operating coil; i denotes contacts of interlocks (position of interlocks is denoted by suffixes 1-4, the top row of contacts being designated No. 1). For example, the "actuating" circuit for step 2 would be read:—Finger 1—No. 2 interlocks, contactor 8—contacts b , accelerating relay—No. 4 interlocks, contactor 8—No. 3 interlocks, contactor 3—coil, contactor 3—No. 1 interlocks, contactor 10—75 ohms—No. 1 interlocks, contactor 9— No. 1 interlocks, contactor 5—earth.

The contacts in the controller are provided with a magnetic blow-out, the blow-out coil being fixed to the back of the arc deflectors. The handle is provided with the "dead-man's handle" feature, and can be locked in the "off" position by the insertion of a key at X.

The master controllers are connected to a special multiple-conductor cable to which the contactor operating coils are also connected. Continuity of this cable between coaches is maintained by a jumper cable with plugs and sockets (Fig. 148), the plugs being arranged so that they can only enter the socket in a certain manner.

All branch connections from the control-circuit cable are made by means of connection boxes with terminals.

FIG. 152.—Front and Back Views of British Westinghouse Electro-magnetic Contactors.

A small cylindrical cut-out switch is inserted in the branch leading to each set of contactors, so that, if necessary, the whole of the operating coils of any group of contactors may be disconnected from the control circuit. The cut-out switches, controlling the motor-controllers on each motor-coach, together with the other switches and fuses for the control and auxiliary circuits, are usually mounted on a slate panel located in the driving compartment of each motor-coach. (See Fig. 286, p. 342.)

With modern control equipments it is customary to instal an electrically-operated circuit-breaker in the circuit of each group of motors. This circuit-breaker follows the general design of the contactors, but is provided with a brush contact, auxiliary (or arcing) contacts, an overload release coil, and a shunt tripping coil. The closing coil is energised from a special switch in the motorman's compartment, and the circuit-breaker is held closed by a latch. It is tripped either automatically,

by the overload coil, or by energising the shunt-trip coil from a switch in the motorman's compartment.

We will now show how the various operations required for the series-parallel control of a pair of motors are carried out. In Fig. 149 is shown a simplified **diagram of connections** for the simplest method of control, using the open-circuit method of transition and an earth return. The master controller has five series notches, five parallel notches, and three transition notches. The chart of switch operations and the key diagram to the motor-circuit connections will enable all the operations of the contactors to be readily followed, so that it is only necessary to make a few remarks concerning the control circuit.

Consider that the reverser is in the "forward" position (as shown

FIG. 153.—Contactor Group, Circuit-breaker, and Rheostats for the Control of Two 275-H.P., 600-volt Motors (British Westinghouse Co.).

in the diagram), and that the train is required to be operated in the reverse direction (for, say, shunting operations). The reversing handle of the master controller is thrown to the "reverse" position and the main handle moved to the first notch. The coil *R* of the reverser is then connected directly across the supply through the interlocks on No. 1 contactor. Thus the reverser is thrown to the "reverse" position, and, at the same time, the auxiliary contacts on the reverser connect the coil *R* in series with the operating coils of contactors 1, 3, 9, the return now being *via* the master-controller cylinder. (Observe that *these contactors can only close provided that No. 10 is open.*) The contactors 1, 3, 9 remain closed on all the series notches.*

On the second notch another path is formed in the control circuit, and No. 4 contactor is operated. On the third notch, contactor 5 is

* In practice contactors 1 and 8 each consist of two contactors connected in parallel, the operating coils being connected in series.

closed, and the operating coil of No. 4 is connected in series with it. Similarly, on the fourth notch No. 6 is operated, the path of the return current being *via* Nos. 5 and 4. On the fifth notch, Nos. 7 and 8 are operated, and are connected in series with Nos. 6, 5, and 4. The transition steps will be readily followed by the aid of the chart in Fig. 149.

On the first parallel notch a circuit is established *via* the coil *R* of the reverser, the operating coils of contactors 1, 2, 10, 11, and the lower segments of master-controller cylinder. Observe that the closing of these contactors *depends on No. 9 being open*, while, when No. 10 is closed, the circuit of No. 9 is interrupted. The object of this interlocking will be apparent from a glance at the key diagram, for Nos. 10 and 11 are parallel contactors, while No. 9 is a series contactor. The remaining parallel notches call for no special observations.

The above method of transition was adopted in the early installations* of the "type M" control system. In modern installations for motor-coach trains the "bridge" transition is universally adopted. This method of transition requires an extra contactor and additional interlocking of the contactors.†

FIG. 154.—Master Controller for British Westinghouse "All Electric" Automatic Control

A simplified diagram of the motor and control-circuit connections for the bridge method of transition is given in Fig. 150.‡ In this diagram the coupler sockets and the auxiliary switches for the control circuit are also shown. The order of closing of the contactors is shown in Fig. 150a, in which the preliminary full-series step should be noted. This step really corresponds to the fifth (or last series) notch on the master controller, and the running notch is obtained automatically, by means of the interlocks on No. 9 contactor. If the control circuit is examined in detail, it will be found that the interlocks on the contactors are of two types—one type in which the auxiliary contacts are closed when the contactor is open, and the other type in which the auxiliary contacts are closed when the contactor is closed.

Considering the control circuit in detail, we have:—

On the first notch a circuit is established through one of the coils of the reverser and the operating coils of contactors 5, 6, 8, 14. Observe that these contactors can only close provided that Nos. 1 and 13

* For example, on the North-Eastern Railway (Newcastle-Tynemouth lines) and the Central London Railway.

† The advantages of "bridge" transition have been discussed in Chapter VIII. For multiple-unit operation the method has the further advantage that the principal contactors and rheostats of a two-motor equipment have only to carry the current of one motor. Compare the motor circuit connections in Figs. 149, 151.

‡ This diagram refers to the B.T.-H. non-automatic control equipments in service on the London Underground Electric Railways.

are open. On the second notch, another circuit is established via the operating coil of contactor 12. On the third notch, the coils of contactors 2 and 11 are connected in series with the coil of No. 12; while, on the fourth and fifth notches, the coils of contactors 3, 10 and 4, 9

FIG. 155.—Views of Accelerating Relay for British Westinghouse Automatic Control.

are added respectively to the series. When No. 9 closes, however, the operating coil of No. 13 is energised; and when this contactor closes, the operating coil of No. 8 is opened automatically by the auxiliary contacts on No. 13. The main current has now a direct path through contactor 13, and consequently the contactors 2, 3, 4, 9, 10, 11, 12 may be opened without interrupting the motor circuit. This operation

takes place on the transition notch. On the first parallel notch a circuit is established from the negative pole of the supply, through the coils of contactors 7 and 1, thence to the positive pole through the operating coils of contactors 5, 6, 14, and the reverser. (The closing of contactor 1 automatically opens contactor 13.) Another path is also formed through the operating coil of contactor 12. The remaining notches operate the contactors 2, 11; 3, 10; and 4, 9.

The interlocks on contactors 5 and 7 are connected in the circuit of the closing coil of the circuit-breaker, so that the latter cannot be closed unless these contactors are open. Moreover, the closing coil of the circuit-breaker is connected, through the master controller, to a

[FIG. 156.—Sectional View of Westinghouse Electro-pneumatic Contactor.

special switch, which is supplied through the master-controller switch (see Fig. 150). Thus, as the latter switches are "off" except at the driving master controller, it follows that the driver has complete control over all the circuit-breakers on the train;* but although these circuit-breakers may be tripped at any notch of the controller, they can only be closed when the master controller is in the "off" position.

The cross-connection of the reverser wires (0 and 8) should be noted. This cross-connection is necessary because the "forward" position of, say, the front master controller must correspond to the "reverse" position of the rear master controller.

Automatic control.—The essential feature of the automatic method of control is the use of relays for controlling the operation of the contactors. The operation of the relays depends on the motor current, so that the

* By means of control wires 5 and 7.

action of the contactors is controlled indirectly by the motor current. The contactors for the first resistance step, and for the series and parallel combinations of the motors, are *operated directly* from the master controller; but the contactors for the succeeding steps in the series and parallel positions are *controlled by the relays*, although the action can be arrested at any point by the master controller.

The **general scheme of operation** is that, as each "resistance contactor" closes, it transfers its operating coil from an *actuating circuit* to a *retaining circuit*, and connects the operating coil of the contactor for the succeeding step to the actuating circuit *via* the contacts of the relays. These contacts are short-circuited when the motor current

FIG. 157.—Sectional View of Operating Cylinder and Valve of Westinghouse Electro-pneumatic Contactor.

is below a predetermined value, but are open-circuited when the motor current exceeds this value. Hence, if the relay contacts are short-circuited, the contactor connected to the actuating circuit will be closed, and will, in turn, transfer its operating coil to the retaining circuit and connect the operating coil of the next contactor to the actuating circuit. Thus, if the master controller is placed in the full-parallel position, the contactors will automatically "notch-up," step by step, until the full-parallel connection is reached, the rate at which the notching progresses being controlled indirectly by the motor current.

Since the resistance steps are only cut out when the motor current falls to the predetermined value, it is possible, by correctly grading the rheostats, to obtain the same variation of motor current on each notch, so that the average accelerating current, and therefore the *average acceleration, will be constant*. It should be noted that this constant average acceleration is obtained not through the skill of the motorman, but through the agency of the relays, combined with the correct grading of the rheostats.

It is apparent that the relays have to fulfil a very important func-

tion, since the acceleration depends on their correct operation. The relays are therefore designed to give reliable operation, and are located in an iron box (see Fig. 286, p. 342), so as to be unaffected by dust, &c.

The **type of relay** adopted for automatic control systems is illustrated in Figs. 155, 286. The relay consists of two potential coils and a current coil, arranged on a common magnetic circuit. Each potential coil is provided with a plunger, which carries a metallic disc capable of short-circuiting a pair of contacts when the plunger is in its lowest position. The plungers are provided with an adjustable time-limit device, the purpose of which is explained below. The potential coils are connected in the circuit of the operating coils of the contactors, and the current coil is connected in the motor circuit.

A simplified diagram of **connections for "Type M" automatic control*** is given in Fig. 151. It will be observed that the majority

FIG. 158.—Group of Westinghouse Electro-pneumatic Contactors.

of the contactors are provided with auxiliary contacts, some of which perform interlocking functions—as in the non-automatic control—while others perform the functions of connecting the operating coils to the actuating and retaining circuits.

The control-circuit cable consists of seven wires, of which five are for the purpose of controlling the contactors, and the remaining two are for the purpose of controlling the automatic circuit-breaker. Each of the wires constituting the control circuit proper has a definite function: thus No. 1 wire controls the "actuating" circuit of the contactors; No. 2 wire controls the "retaining" circuit of the contactors; No. 3 wire controls the transition into parallel; and wires Nos. 8 and 0 control respectively the "forward" and "reverse" operating coils of the reverser, as well as the "trolley" and "ground" contactors (Nos. 1 and 4).

When the master controller is placed on the first (series) notch "forward," two circuits are established. One circuit is from No. 8 finger, through the "forward" operating coil and interlocks of the

* This system of control has recently been installed by the British Thomson-Houston Co. on some of the trains operating on the Central London and the London Underground Railways. It should be remarked that the automatic features were originally developed by Mr. F. J. Sprague, and that the automatic control system is designated as the *Sprague-Thomson-Houston* (or *Sprague-General Electric*) *Control System (Form M)*.

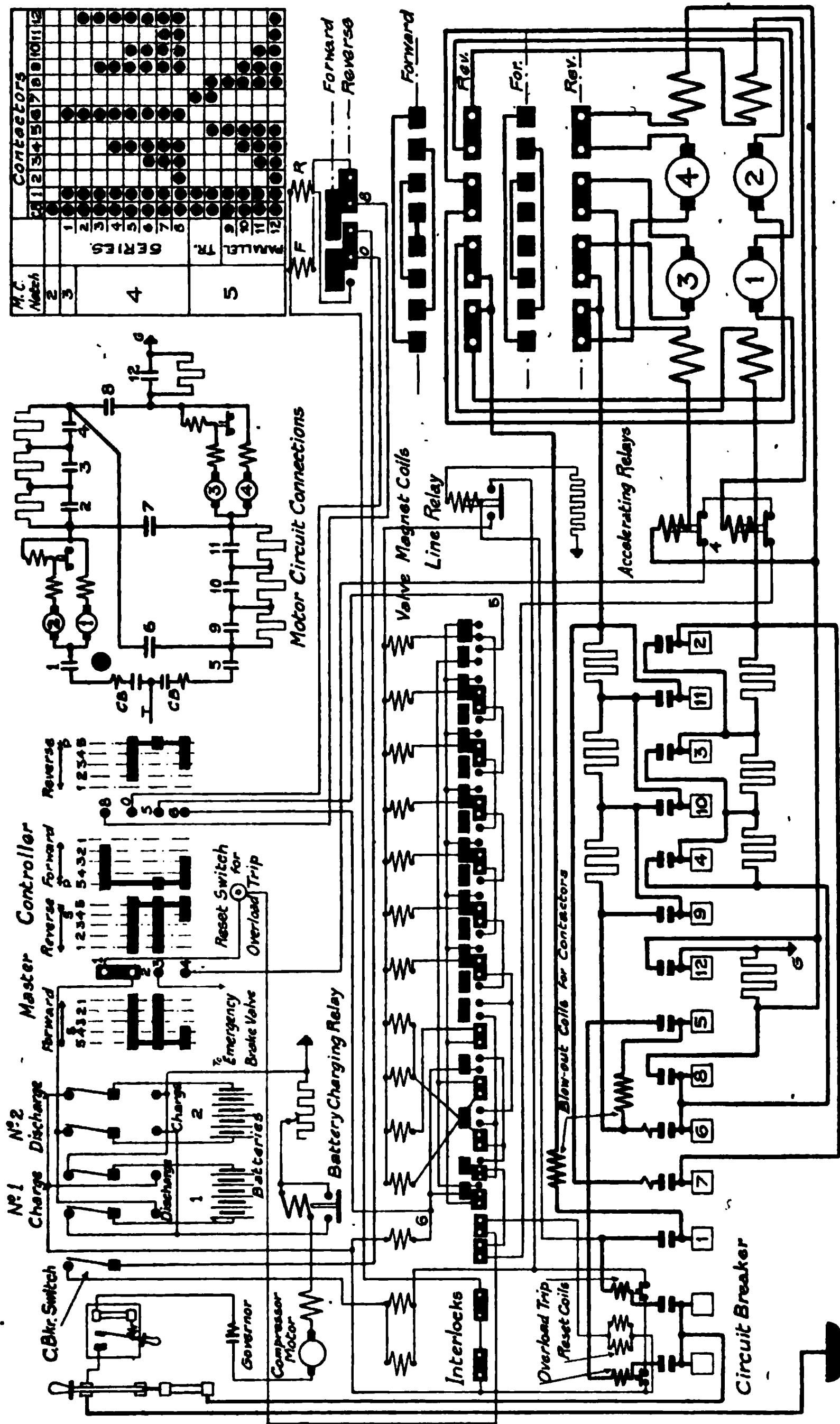


FIG. 159.—Connections for Westinghouse Electro-pneumatic Control System with Battery. NOTE.—The control-circuit cable and couplers are omitted. The interlocks are shown in the "open" position of the contactors.

reverser,* through the operating coils of contactors 1 and 4, and thence to earth through a rheostat coil. The other circuit is from No. 2 finger,† through the contacts of the “line relay,”‡ and thence through the operating coil of “series” contactor (No. 8) to earth *via* the auxiliary contacts of contactors 1, 7, 6, 3, 10, 9, 2, 11, 5, and a number of rheostat coils. Observe that this circuit is not complete until the line relay and contactor 1 close, also that the closing of the line relay is dependent on the circuit-breaker and main switch being closed, and sufficient voltage at the collector shoes.

If the master controller is held on the first notch, only contactors 1, 4, 8 are closed. The motors are therefore connected in series with all the rheostats in circuit.

If the master controller is moved to the second notch, another circuit (called the “actuating” circuit) is established by means of wire No. 1 and the automatic accelerating relay. This circuit, however, is under the control of the relay, and the contactors will only be energised provided that the relay contacts are short-circuited, which occurs when the motor current is below a predetermined value.§

Assuming that these contacts are closed when the master controller is moved to the second notch, a circuit will be established through the operating coil of No. 3 contactor to earth *via* the auxiliary contacts (*b*) of the relay and contactors 8, 3, 10, 9, 2, 11, 5. When contactor 3 closes, the auxiliary contacts on this contactor transfer the operating coil to the “retaining” circuit (energised from No. 2 wire).

The increase of current in the motor circuit, due to cutting-out a section of the rheostats, will cause the relay to operate, but the plungers are fitted with a time-limit device which retards the operation of the relay—and therefore the opening of the “actuating” circuit (No. 1 wire)—until the contactor coil has been transferred to the “retaining” circuit by means of the auxiliary contacts on the contactor.

When the relay contacts close again, contactor 10 is energised *via* the auxiliary contacts (*c*) of the relay and contactors 8, 12, 6, 10, 3, 9, 2, 11, 5.

Next, contactor 2 is energised *via* the auxiliary contacts (*b*) of the relay and contactors 8, 9, 2, 10, 11, 5.

In a similar manner contactor 11, and contactors 5 and 9, are ener-

* If the reverser is in the “reverse” position, the “forward” coil is energised with the full line voltage (as above), provided that No. 4 contactor is open.

† This circuit (from No. 2 finger) forms the “retaining” circuit for the contactors which are energised automatically when the master controller is moved to either the second or the fourth notch.

‡ The object of the line relay (which forms part of the control equipment of each motor-coach) is to interrupt the control circuit when the voltage is removed from the motor circuit. For instance, if a train of several motor-coaches is operated without a “bus-line” cable (*i.e.* a cable interconnecting the collector shoes, of like polarity, throughout the train), the motor circuits are supplied through the individual collector shoes on each motor-coach, while the whole of the control circuits are supplied from the driving coach. Hence if, say, the rear motor-coach passes over a dead section, the line relay interrupts the control circuit on that coach, and closes it again automatically when the voltage is restored to the collector shoes. The contactors, therefore, must “notch-up” again in the same manner as if they were controlled by the master controller.

§ An automatic accelerating relay forms part of the control equipment of each motor-coach. Hence the contactors on any individual motor-coach of a train are *under the control of the accelerating relay on that coach*, and cannot be operated by the relays on other coaches.

gised respectively on the next two notches. The transference of the earth connection of the "retaining" circuit from No. 5 contactor to No. 9 contactor should be noted, as well as the automatic opening of contactors 2 and 11. The table on page 179 will facilitate the tracing of the circuits.

Forward
Reverse
Master Controller

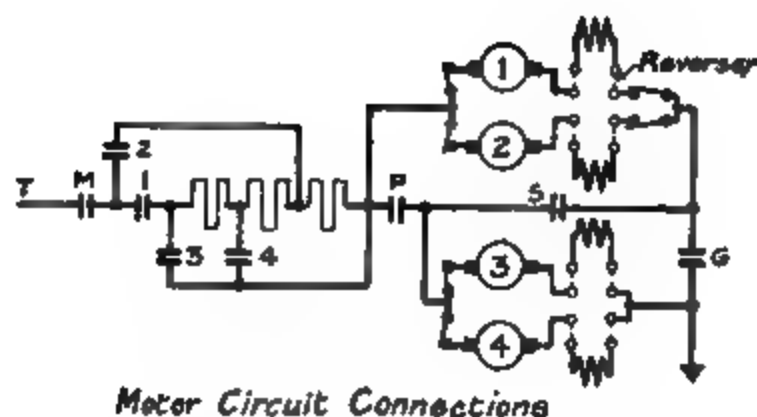


FIG. 160.—Connections for Westinghouse Electro-pneumatic Control System without Battery. NOTE.—The interlocks are shown in the "open" position of the contactors.

On the next notch—the last series notch—the "bridge" contactor (No. 6) is energised, and when this contactor closes, its auxiliary contacts open the circuit of contactors 3, 5, 8, 9, 10. The contactors closed on the last series notch are, therefore, Nos. 1, 4, 6.

It should be noted that no more "notching-up" can take place unless No. 3 wire is energised. Moreover, it will have been observed

that, during the above process of notching-up, the notching can be stopped at any desired point by placing the master controller on the first notch, which interrupts the "actuating" circuit.

If the master controller is moved to the last (or fourth) notch "forward," contactors 7 and 12 will be energised from No. 3 wire *via* the auxiliary contacts (*b*) of the relay and contactors 6, 8, 7, 3, 10, 2, 11, 5.

FIG. 161.—Front and Back Views of Westinghouse Electro-pneumatic Contactor-group for Four-motor Equipments (75 H.P. Motors).

When contactors 7 and 12 close, the control circuit is transferred to No. 2 wire *via* the auxiliary contacts of the line relay and contactors 1, 7, 8, 3, 10, 2, 11, 5. Thus the object of No. 3 wire is to energise the "parallel" contactors (Nos. 7 and 12), and these contactors cannot close until No. 6 has closed and No. 8 has opened. At starting, the master controller may be placed directly on the last notch, and "notching-up" will take place through all the series notches, the transition notch, and the parallel notches.

FIG. 162.—Views of Control-box for Westinghouse Combined Contactor and Drum Control System. The upper view shows the drum controller and the overload relay; the lower view shows the reverser and the accelerating relay.

When No. 7 contactor closes, No. 6 contactor is automatically opened, and the potential coils of the relay are supplied through the auxiliary contacts of No. 7 contactor. On the series notches the potential coils of the relay are supplied through the auxiliary contacts of No. 8 contactor. Thus the automatic relay can only control the "actuating" circuit, provided that *either* No. 8 or No. 7 contactor is closed.

The notching-up to "full parallel" will take place in a manner similar to that for the series steps, and can be followed easily from the chart of switching operations, and the table on page 179.*

The provision of duplicate potential coils and contacts on the relay ensures that the control connections are made in the correct order.

The important contactors (*e.g.* Nos. 1, 7, 12, 8, 6) are interlocked in a manner similar to that described above in connection with Fig. 150, while the closing coil of the circuit-breaker is interlocked with No. 1 contactor, and can only be energised when this contactor is open.

The British Westinghouse Co.'s "All-Electric" Automatic System of Control.—This system of control provides for automatic acceleration, and resembles the Type M automatic control in many features. As the general method of operation is practically identical in the two cases, we shall only discuss the control apparatus.

The first installation of this ("all-electric") system of control by the Westinghouse Co. has been carried out for the electrification of the London suburban lines of the London and South-Western Railway. In previous installations—such as the Metropolitan (London) and Mersey Railways—the electro-pneumatic system, described below, has been adopted.

The **contactors** differ only in constructional features from the contactors for Type M control, the general features and method of operation being common to both types. Typical views of a contactor are shown in Fig. 152. In these illustrations the main contacts and terminals, the blow-out coil, and the auxiliary contacts can be clearly seen. Twelve contactors are provided for the series-parallel control of each pair of motors,† and the contactors are mounted on an iron framework in the driver's compartment. On this framework are also mounted the rheostats and the circuit-breaker, as shown in Fig. 153.

The **reverser** is of the throw-over drum type, and is operated by solenoids. The main segments are fixed to castings, which are clamped to a mica-insulated square shaft, and the fingers for the motor and control circuits are fixed to mica-insulated bars. The interlocking is carried out by means of an additional contact drum, which is fixed to the same shaft as the main drum, and a set of fingers.

The **master controller** is provided with both main and reversing handles. The reversing cylinder is concentric with the main cylinder (see Fig. 154), so that the fingers for both cylinders can be fixed to one

* Observe that when the motors are in parallel the operation of the contactors is governed by the current in motor No. 1. On some of the parallel notches the closing of corresponding "resistance" contactors takes place successively instead of simultaneously as with non-automatic control. For example, a rheostat section in No. 1 motor circuit is not cut out until the contactor of the corresponding section in No. 2 motor circuit is fully closed. The next rheostat section in No. 2 motor circuit, however, cannot be cut out until the relay contacts close again.

† Each motor is rated at 275 H.P., 600 volts.

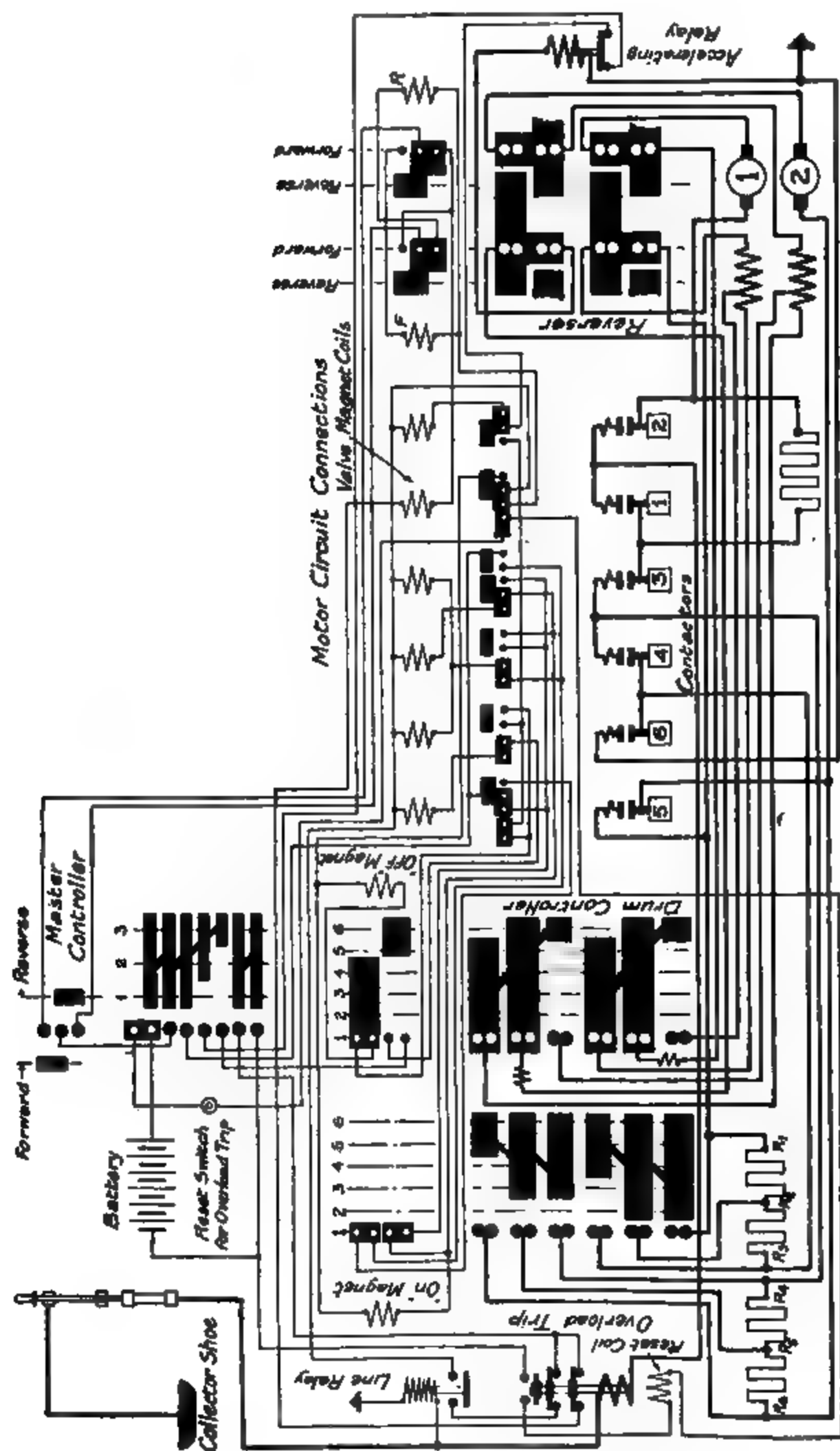


FIG. 163.—Connections for Westinghouse Electro-pneumatic Control System using Contactors and a Pneumatically-operated Drum Controller.

mica-insulated bar. The link-work for operating the reversing cylinder, and the interlocking mechanism between this cylinder and the power cylinder, can be seen in the illustration. The main operating handle is provided with the "dead-man's handle" feature, and the release of the handle on any power notch automatically returns the main cylinder to the "off" position and applies the brakes. The handle must then be returned to the "off" position and depressed before the main cylinder can be operated again. The automatic feature is also operative in the "off" position of the main handle, so that it is necessary for the motor-man to retain his hold of this handle.*

The master controller is arranged with four notches, viz. two series and two parallel, and the operations performed on these notches are identical with those for the "forward" notches of the controller illustrated in Fig. 147.

The automatic accelerating relay is illustrated in Fig. 155.

The Westinghouse Electro-Pneumatic System.†—The special feature of this system is that the contactors are operated pneumatically, and the supply of air to the pneumatic cylinders is controlled by electro-magnetic valves which are energised from a low-voltage circuit by a suitable master controller. The electro-pneumatic feature has been developed extensively by the Westinghouse Companies for all classes of railway control apparatus, and further examples of the application of this system will be found in Chapters X, XI.

FIG. 164. -Westinghouse Series-parallel Controller with Electro-pneumatic Operating Gear.

The control equipment includes a group of electro-pneumatic contactors (called a "switch group"), an electro-pneumatic reverser, a master controller, duplicate 14-volt storage batteries,‡ the necessary control-circuit cables and switchgear, and, in some cases, relays for automatic acceleration.

A sectional view of a **contactor** or "unit switch" is shown in Fig. 156, while a detailed view of the pneumatic cylinder and the electro-magnetic controlling valve is shown in Fig. 157.§ The cylinder *A* is single-acting,

* The automatic device may be rendered inoperative in the "off" position of the main handle by placing the reversing handle in the "off" position.

† This system of control is adopted on the Westinghouse equipments in service on the Metropolitan Railway.

‡ On the Metropolitan Railway the batteries have been replaced by small motor generator sets.

§ See Fig. 165 for a cross-section of the valve.

and the piston *B* moves against a strong spring. An insulated extension of the piston-rod engages a pin fixed to the lever to which the lower main contact is pivoted, while a projection *D* is provided for carrying the segments of the auxiliary contacts. The admission valve *V* is maintained on its seat by a spring, and is opened by the plunger of the ironclad solenoid *S*. This plunger also controls the exhaust valve (see Fig. 165, "on" magnet). When the solenoid is energised, the cylinder is supplied with compressed air at a pressure of about 70 lb. per sq. in., and the main contacts are closed with considerable pressure, the contacts closing with a wiping action. The main contacts are located in an arc chute, of fireproof material, and are provided with a blow-out coil.

The requisite number of contactors for the control of a pair of motors are built into a common frame to form a "switch group," a typical example

FIG. 165.—Section of Pneumatic Cylinder and Valves for Westinghouse P.K. Control.

being shown in Fig. 158.* This illustration refers to a switch group for the control of four 150-H.P. motors on the series-parallel system with bridge transition and automatic acceleration, and is representative of the Westinghouse control equipments in service on the Metropolitan Railway (London).

A simplified diagram of the connections for this switch-group is shown in Fig. 159, in which the extreme simplicity of the master controller should be noted.

The control circuit is supplied from a 14-volt storage battery. A duplicate battery is provided, so that one battery is always available while the other is being charged, this operation being performed by connecting the battery in series with either the lighting circuit of the coach, or the motor driving the air-compressor. Two double-throw switches provide the interchange of the connections for the batteries.

Although the batteries provide a convenient method of supplying the small coils of the valve magnets at a suitable voltage, their use, in

* For further descriptive information and illustrations of Westinghouse electro-pneumatic control apparatus see *Electric Journal*, vols. 7, p. 802; 8, p. 890; 9, p. 929; 10, pp. 970, 1045; 11, p. 570; 12, p. 452.

some cases, is considered to be undesirable. In these cases the low voltage may be obtained from a tapping on a resistance connected across the supply system, and a simplification of the control apparatus thereby results, since the battery switches are eliminated. This method of supplying the control circuit has been standardised by the Westinghouse

FIG. 160.—Connections for Westinghouse P.K. Multiple-unit Control.

Co. for the control equipments of single inter-urban cars, on which the motor equipment is usually four 75-H.P. motors. A **diagram of the connections** for this equipment is given in Fig. 160. It will be observed that only eight contactors are required, although five series notches and four parallel notches are provided. The method of connecting the sections of the rheostat in series and parallel should also be observed. Since only one group of rheostats are used, it is apparent

that the bridge method of transition is not adopted. An inspection of the chart of switching operations will show that the transition is effected by short-circuiting a pair of motors.

Views of the switch group are given in Fig. 161. These views also illustrate the method of mounting the pneumatic cylinders on the common frame, and the arrangement of the valves.

As the control is non-automatic, interlocks are only required on the series (*S*) and parallel (*P*) contactors.

An interesting combination of contactors with a pneumatically-operated drum controller has recently been developed by the Westinghouse Co. for the New York Municipal and Interborough Rapid Transit Railways. These equipments* are arranged for automatic acceleration and field control.

Views of the control equipment are given in Fig. 162, and a simplified diagram of connections is given in Fig. 163.

It will be observed that contactors are only used for the operations connected with the grouping of the motors, the whole of the notching operations for the resistance steps and field control being carried out by a drum-type controller. In this manner the number of contactors is reduced to six,† notwithstanding that a total of ten notches are provided (viz. six series and four parallel), and that the bridge method of transition is adopted.

The drum controller, together with the overload relay, are fixed at one end of the switch group, while at the other end are fixed the reverser and the current-limiting relay. Thus the whole of the motor-controller is a self-contained piece of apparatus. The overall length of this apparatus is 4 ft., of which the switch group occupies 2 ft. 8 in.

In normal operation the contacts of the drum controller are not subjected to arcing, since the breaking of the circuits is performed by the contactors. The contacts controlling the field connections, however, are provided with a magnetic blow-out, in order to protect them in the event of an open-circuit in the field tapplings.

The drum controller is actuated by pneumatic cylinders in the manner described below. Interlocks are provided on this controller, the contactors, and the reverser to ensure correct operation.

The master controller supplies the control circuit from a 34-volt battery.‡

Electro-pneumatic Drum Controllers.—Although the electro-pneumatic operation of a series-parallel drum-type controller was developed (for multiple unit working) by the Westinghouse Co. a number of years ago,§ and abandoned in favour of electro-pneumatic contactors, the principle has recently been re-introduced for small equipments.

* The motors are rated at 160 H.P., 600 volts. For further details of the cars and equipment see *Electric Railway Journal*, vols. 43, p. 1261, p. 1327; 44, p. 1376; 45, p. 496.

† If the control notches had been obtained by contactors only, a total of 14 would have been required.

‡ The battery supplies also the signal lights, door circuit interlocks, and brake circuits. The increase in voltage (from the standard of 14 volts) was necessary on account of these features and the long length of train, which may consist of a maximum of fifteen 67 ft. coaches.

§ This system of control is in service on the Mersey Railway. For a description of the controllers and method of operation see *The Electrical Review*, vol. 49, p. 975; *The Electrician*, vol. 51, p. 5.

The multiple-unit operation of a number of small cars can, therefore, be obtained by the addition of an operating head to the existing controllers, and the provision of master controllers and the necessary control-circuit cable.

In these equipments *—which have been supplied to the New York street railways—the standard platform controller is fitted with an **operating head** (as shown in Fig. 164), and the controller is operated electro-pneumatically from a master controller. Only one main con-

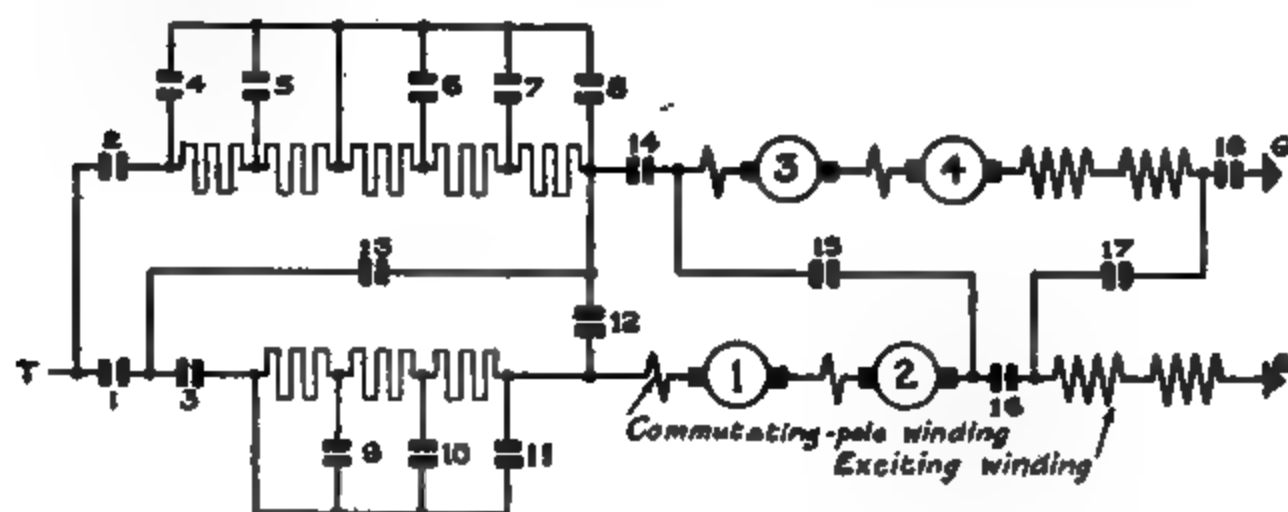


FIG. 167.—Motor Circuit Connections for Control of Motors on 2400-volt Circuit.

NOTE.—The [commutating-pole windings are usually connected—with the exciting windings—on the earthed side of the armatures.

troller is therefore necessary on the car, and, since this controller is remote controlled, it may be located in any convenient part of the car. The main cylinder is operated by means of a rack and pinion, as shown in Fig. 165. The rack forms the piston-rod for two pistons, which operate in a double-acting pneumatic cylinder. The air supply to this cylinder is controlled by electro-magnetic valves which are energised from the master controller. The "on" magnet (Fig. 165) admits compressed air to the "on" cylinder, and the "off" magnet, when energised, releases the air from the "off" cylinder. The forward movement of the controller drum is obtained by energising both magnets simultane-

* Designated by the Westinghouse Co. as *P.K. Control equipments*.

ously. The return movement of this drum is obtained by cutting off the current from the valve magnets, which results in the admission of air to the "off" cylinder and the release of the air in the "on" cylinder. To stop the movement of the controller drum, the air pressure in the "on" and "off" cylinders is equalised.

In order to obtain the correct notches on the controller, the control circuit of the "off" magnet is broken on an auxiliary interlocking drum, which is connected to an extension of the controller shaft. The positions of the segments on this drum correspond to the notches on the main drum, and the fingers corresponding to these segments are supplied from the master controller through separate wires, as shown in Fig. 166.

The reversing drum of the controller is also operated by a double-acting cylinder. In this case the piston-rod is connected to a crank, and another crank on the same shaft is connected, by a link, to a crank on the shaft of the reversing drum. The air supply to the cylinder is controlled by two electro-magnetic valves. When one magnet is energised, the reversing drum is thrown to the "forward" position; and when the other magnet is energised, the reversing drum is thrown to the "reverse" position. The control of these magnets is, of course, carried out from the reversing drum on the master controller.

The system of control has been developed to provide for automatic acceleration, and the master controller is arranged with a "dead-man's handle." In order to obtain these automatic features from the drum-controller equipment, a current-limiting relay and two electro-pneumatic contactors are provided. These contactors also act as an effective circuit breaker.

In Fig. 166 are given the connections for the control and motor circuits. A reference to the diagram of the motor-circuit connections will show that field control is adopted.

An inspection of Fig. 164 will show that each of the fingers for the main drum of the controller is provided with a blow-out coil. The blow-out coils have iron cores, and iron flanges are fixed to the core on each side of the coil. Iron plates are also embedded in the arc deflectors, so that a very efficient blow-out is produced. This type of blow-out (which may be called the **individual blow-out**) is used for drum controllers handling heavy currents, and has the advantage that the strength

FIG. 168.—B.T.-H. Contactor for 2400-volt Circuits.

of the blow-out field on any finger can be proportioned to the current to be broken.

The control of motors on high-voltage circuits.—With railways operating at voltages above 1200 volts it is general practice to connect two motors permanently in series. The series connection of the motors, however, is not essential on circuits of 1200 and 1500 volts, as motors capable of operating directly at these voltages are now manufactured and are in service.

With motors operating at the full line voltage the control is carried out by the series-parallel system; but when two motors are permanently connected in series, the control is usually carried out by the series, series parallel system, each group of two motors being connected either in series or in parallel with a similar group.

The transition from series to series-parallel is effected by short-circuiting a pair of motors, so that the main circuit is not opened in transition. The connections may be arranged as shown diagrammatically in Fig. 167, which with the chart of switching operations is self-explanatory.

The control apparatus for high-voltage motors must, obviously, be remote controlled. Generally the method of operating the control apparatus follows the practice adopted with the multiple-unit systems described above, the voltage for the control circuit being obtained from either a rotary transformer or a reducer (called a dynamotor, see Chapter XIV). This machine also supplies the compressor motor, and the lighting and heating circuits.

FIG. 169.—Dick-Kerr High-voltage and Low-voltage Contactors.

The contactors may be either of the electro-magnetic or the electro-pneumatic types, and differ from those described above in two features, viz. (1) the additional insulation, and (2) the larger arc chutes.

Views of typical high-voltage contactors are shown in Figs. 168, 169.

The contactor shown in Fig. 168 has been developed, by the General Electric Co. and the British Thomson-Houston Co., for circuits of 2400 volts. The upper (fixed) contact is mounted on insulators, and the movable contact is operated through a connecting-rod of treated hickory wood, the hinge for this contact being fixed to the insulators carrying the fixed contact. Both terminals of the contactor are therefore insulated, and the frame is usually earthed. The main contacts are provided with a magnetic blow-out and a large, narrow arc chute. Auxiliary

contacts are provided for interlocking the control circuit of the principal contactors.

When contactors of this type are installed on 2400-volt locomotives, it is general practice to connect two or three contactors in series at points in the motor circuit where current has to be broken at high voltage (as, for example, at contactors 1, 2, 14, 15 in Fig. 167). In this manner the contactors are capable of breaking currents considerably in excess of the normal current without excessive burning of the main contacts.*

The contactor group shown in Fig. 169 illustrates the high-voltage and low-voltage contactors developed by Messrs. Dick, Kerr & Co. The illustration refers to a portion of the control equipment—in service on the 3750-volt experimental line of the Lancashire and Yorkshire Railway (Bury-Holcombe Brook)—for controlling four 300 H.P. 1875-volt motors on the series, series-parallel system.

The two upper contactors are each capable of rupturing the total current taken by the equipment, and have been tested successfully at 5000 volts. Under service conditions, the circuit is broken by two contactors in series. The three lower contactors are of Messrs. Dick, Kerr's standard 600-volt type.

All the contactors are provided with the Dick-Kerr metallic-shield blow-out (described in Chapter VIII). The blow-out coils, pole-cores, pole-pieces, and shields are shown clearly in Fig. 169. [NOTE.—The blow-out coil and shield have been removed from the centre contactor of the lower group.] The elongated blow-out coil and the special arc chute of the high-voltage contactor should be noted.

The main contacts are shown at the lower part of the contactors, the fixed contacts being on the right. Of these contacts, the lower one is for carrying the current, the intermediate or auxiliary contact is the one at which the circuit is made and broken, and the upper contact (located in the arc chute) is for taking the arcing when the circuit is broken.

The shaft carrying the movable contact is arranged horizontally in bearings, and is given a rotary motion (through a small arc) by means of an electro-magnet at the back of the contactor. The arcing finger is fixed, and is connected to the movable finger by flexible copper shunts.

When current is broken by the contactor, the arc formed between the movable and auxiliary contacts is immediately blown on to the special arcing contacts, and is then extended around the shield until it is ruptured.

THE CALCULATION OF THE RESISTANCE SECTIONS OF STARTING RHEOSTATS FOR CONTINUOUS-CURRENT MOTORS

A reference to the connection diagrams of series-parallel controllers will show that the starting rheostats must be arranged with a limited number of sections, and that some of the sections must be suitable for use with both the series and the parallel positions of the controller. Modern tramway controllers have the starting portion of the rheostats divided into four sections, of which three are common to the series and parallel notches. With

* It should be observed that the control equipment of a locomotive is subjected to much harder usage than the control equipment of a motor-coach, as the locomotive may be required to operate on shunting service, which subjects the "trolley" contactors to very heavy duty.

the bridge method of transition and multiple-unit control—as adopted for motor-coach trains—seven rheostat sections are usually provided.

In selecting the number of sections for use with a given motor equipment we have to consider the maximum tractive-effort which may be exerted during the starting period, as well as the permissible variation of the tractive-effort. These considerations involve others, such as the adhesive weight * of the train, locomotive, or car; the coefficient of adhesion; * the mass to be accelerated; and the gradients (if any) which have to be negotiated.

With tramcars the adhesive weight is from 75 per cent. to 100 per cent.

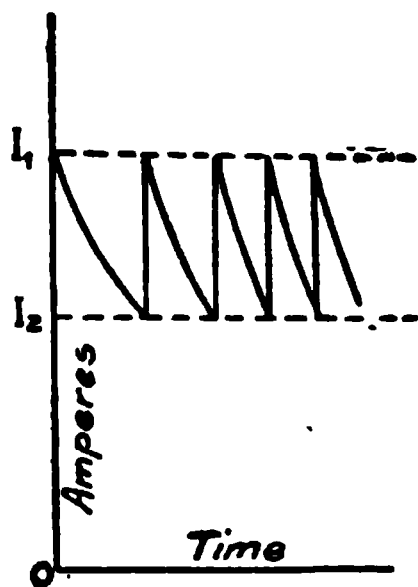


FIG. 170.

of the weight of the car, while with motor-coach trains the adhesive weight is usually of the order of 50 per cent. of the weight of the train. Generally, in each of these cases, the mean accelerating tractive-effort is considerably below that required to slip the driving wheels under normal conditions (i.e. with dry rails). Therefore, as far as the design of the starting rheostats is concerned, relatively large fluctuations in the tractive-effort are permissible, so that only a few notches are required on the controller.

On the other hand, with electric locomotives, the tractive-effort required for acceleration may approach the limiting value at which slipping of the driving wheels occurs, so that only a relatively small variation of the tractive-effort will be permissible during starting.†

When the maximum tractive-effort and the variation of the tractive-effort are given, the corresponding currents can be obtained from the characteristic curves of the motor. The number of sections and the grading of the rheostats can then be calculated. The calculations, however, become considerably involved when exact values are required, the complication being due to the variation of the flux with the current.

Let us investigate the case for the series-parallel control of two motors using "bridge" transition (see Fig. 118). The mean tractive-effort during the starting period is to be constant. It will, therefore, be desirable for equal variations of the tractive-effort to occur on the several series and parallel notches, although the variations for the parallel notches will not necessarily be the same as those for the series notches. The maximum and minimum currents *per motor* corresponding to these variations of tractive-effort will be denoted respectively by I_1 , I_2 for the series notches, and by I'_1 , I'_2 for the parallel notches, the mean accelerating current per motor (I) being the same for all notches.

The rheostat sections must therefore be designed so that, in passing from notch to notch, the current will increase from I_2 to I_1 on the series notches (see Fig. 170), and from I'_2 to I'_1 on the parallel notches.

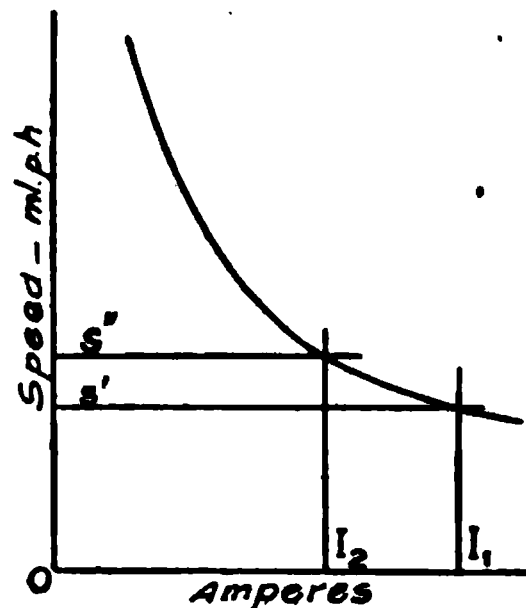


FIG. 171.

Let n , n' denote the number of rheostat sections for the series and parallel notches respectively; ‡

R_1 , R_2 , . . . R_n the external resistance in circuit with the motors on the several series notches; R'_1 , R'_2 , . . . $R'_{n'}$ the corresponding values (for *each* motor) § for the parallel notches; and r the internal resistance of one motor.

* See Chapter XVII, p. 356.

† With freight locomotives, large variations of the tractive-effort during starting must be avoided, otherwise breakage of the couplings may occur.

‡ The number of notches will be $(n+1)$ and $(n'+1)$.

§ Observe that, with bridge transition, rheostats are inserted in circuit with *each* motor on the parallel notches (see Fig. 118). Contrast with the other methods of transition shown in Figs. 116, 117.

Then, assuming that the maximum current I_1 is obtained on the first series notch, we have, if V denotes the voltage of the supply circuit,

$$I_1 = V/(R_1 + 2r)$$

The speed now increases until I_1 has decreased to I_2 , when the controller is moved to the second notch.

In passing from the first to the second notch the speed is unchanged. Hence, if s_1, s_2 denote the speeds (at normal voltage $-V$) corresponding to the currents I_1, I_2 (see Fig. 171); and ${}_1s_1, {}_1s_2, {}_2s_1, {}_2s_2$ denote the speeds corresponding to these currents on the first and second series notches, then ${}_1s_1 = 0$;

$${}_1s_2 = s_2 \left\{ \frac{V - I_2(R_1 + 2r)}{2(V - I_2r)} \right\}; \quad {}_2s_1 = s_1 \left\{ \frac{V - I_1(R_2 + 2r)}{2(V - I_1r)} \right\}; \quad {}_2s_2 = s_2 \left\{ \frac{V - I_2(R_2 + 2r)}{2(V - I_2r)} \right\}.$$

But ${}_1s_2 = {}_2s_1$, hence

$$\frac{s_1(V - I_2r)}{s_2(V - I_1r)} = \frac{V - I_2(R_1 + 2r)}{V - I_1(R_2 + 2r)}$$

In passing from the second to the third notch we have ${}_2s_2 = {}_3s_1$, and by a similar process we obtain:

$$\frac{s_1(V - I_2r)}{s_2(V - I_1r)} = \frac{V - I_2(R_2 + 2r)}{V - I_1(R_3 + 2r)}$$

Finally, in passing from the n th notch to the $(n+1)$ th notch (which is the last series notch), we have:

$$\frac{s_1(V - I_2r)}{s_2(V - I_1r)} = \frac{V - I_2(R_n + 2r)}{V - 2I_1r}$$

The speed corresponding to a current I_2 on the last series notch is given by:

$${}_{(n+1)}s_2 = s_2 \left\{ \frac{V - 2I_2r}{2(V - I_2r)} \right\},$$

and if transition into parallel is effected at this speed we have:

$${}_1s'_1 = s'_1 \left\{ \frac{V - I'_1(R'_1 + r)}{V - I'_1r} \right\},$$

where the dashed symbols refer to the parallel notches.

Hence, as ${}_{(n+1)}s_2 = {}_1s'_1$, we obtain:

$$\frac{2s'_1(V - I_2r)}{s_2(V - I'_1r)} = \frac{V - 2I_2r}{V - I'_1(R'_1 + r)}.$$

In passing from the first to the second of the parallel notches we obtain, by a process similar to the above:

$$\frac{s'_1(V - I'_2r)}{s'_2(V - I'_1r)} = \frac{V - I'_2(R'_1 + r)}{V - I'_1(R'_2 + r)}$$

Therefore for the series notches the general equations are:

$$\frac{s_1(V - I_2r)}{s_2(V - I_1r)} = \frac{V - I_2(R_1 + 2r)}{V - I_1(R_2 + 2r)} = \dots = \frac{V - I_2(R_n + 2r)}{V - 2I_1r} \dots \quad (31)$$

while for the parallel notches the general equations are:

$$\frac{s'_1(V - I'_2r)}{s'_2(V - I'_1r)} = \frac{V - I'_2(R'_1 + r)}{V - I'_1(R'_2 + r)} = \dots = \frac{V - I'_2(R'_n + r)}{V - I'_1r} \dots \quad (32)$$

and

$$\frac{2s'_1(V - I_2r)}{s_2(V - I'_1r)} = \frac{V - 2I_2r}{V - I'_1(R'_1 + r)} \dots \quad (32a)$$

The solution of these equations may be obtained either by trial or by means of graphical methods.* In each case it will be necessary to assume values for I_1, I_2, I'_1, I'_2 , and to have available the speed curve of the motor.

* See *Electric Railway Journal*, vol. 44, p. 1382, for a graphical method of solution.

If the number of notches is given—which is usually the case in practice—then the values assumed for I_1 , I_2 , I'_1 , I'_2 must enable the equations (31), (32) to be completely satisfied.

[NOTE.—The total resistances R_1 , R'_1 of the series and parallel portions of the rheostats are obtained by the application of the equations:

$$I_1 = \frac{V}{R_1 + 2r} \quad \text{and} \quad \frac{2s'_1(V - I_2r)}{s_2(V - I'_1r)} = \frac{V - 2I_2r}{V - I'_1(R'_1 + r)};$$

while the resistances (R_2, \dots, R_n ; R'_2, \dots, R'_n) for the other notches are obtained by successive substitution in the general equations (31), (32).]

The method of solution by trial is therefore a lengthy process.

In cases where the conditions of service are not severe (e.g. on tramways) an **approximate solution** to the above equations may be obtained by assuming that the flux in the motor is constant between the maximum and minimum values of the starting current. Equation (31) then reduces to:

$$\frac{I_1}{I_2} = \frac{R_1 + 2r}{R_2 + 2r} = \frac{R_2 + 2r}{R_3 + 2r} = \dots = \frac{R_n + 2r}{2r} \quad (31a)$$

which is a simple geometrical progression.

Hence $\left(\frac{I_1}{I_2}\right)^n = \frac{R_1 + 2r}{2r}$. But $R_1 + 2r = V/I_1$. Therefore I_2 can be readily determined, and the values of R_2, R_3, \dots can be easily evaluated.

With tramcar controllers the rheostats in the parallel notches are connected in series with a pair of motors (see Fig. 129), so that the total resistances of the motors and rheostats on the several notches are $R'_1 + \frac{1}{2}r$, $R'_2 + \frac{1}{2}r$, &c. Hence equation (32) reduces to:

$$\frac{I'_1}{I'_2} = \frac{R'_1 + \frac{1}{2}r}{R'_2 + \frac{1}{2}r} = \dots = \frac{R'_n + \frac{1}{2}r}{\frac{1}{2}r} \quad (32b)$$

Therefore $\left(\frac{I'_1}{I'_2}\right)^n = \frac{R'_1 + \frac{1}{2}r}{\frac{1}{2}r}$

By simplifying equation (32a) we obtain:

$$R'_1 + \frac{1}{2}r = \frac{V + 2I_2r}{2I'_1} \quad (32c)$$

The calculation of the rheostat sections in this case presents no difficulty, and it is only necessary to adjust the resistances so that some of the sections may be used in both the series and the parallel notches.

The approximate method of rheostat design, however, does not result in the attainment of uniformly high current-peaks on the several notches, and it is not suitable for railway service in which, to avoid slipping of the driving wheels, uniformly high current-peaks are essential.

It may be remarked that in practice the resistance of the rheostats and the number of sections is influenced by the slope of the speed curve at the mean accelerating current. A motor possessing a steep speed curve (e.g. a single-phase motor, or a continuous-current motor with either an unsaturated magnetic circuit or a high resistance) will require fewer rheostat sections (for a given percentage variation of tractive-effort) than a motor possessing a flat speed curve. This feature is shown in Figs. 172, 173. Fig. 172 also shows that, for an equal number of notches in the series and parallel positions of the controller, the variation of tractive-effort will be greater for the series notches than for the parallel notches, due to the smaller slope of the "series" speed curve.

The design of rheostats for use with electric locomotives usually differs in several features from that of rheostats for use with motor-coach trains. The distinction arises from the fact that with motor coach trains the adhesive weight (for a given train) is only slightly affected by variations

* I_1 , I'_2 , in this case, refer to the line currents, and R'_1 , R'_2, \dots refer to the rheostats in series with a pair of motors.

in the train weight (see Table XI, p. 325), so that, for a given mean accelerating current, the acceleration of a lightly-loaded train will not differ ap-

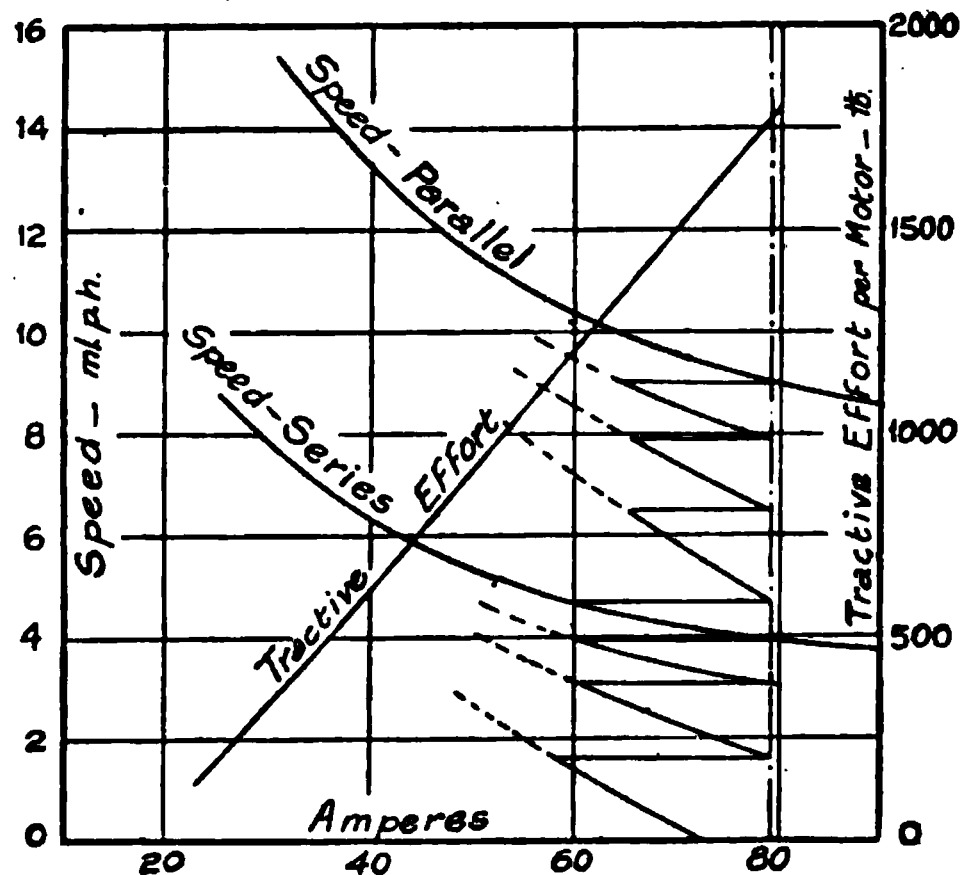


FIG. 172.—Showing the fluctuations in speed and current per motor during starting two 40-H.P. Tramway Motors.

preciably from that of a fully-loaded train. On the other hand, a locomotive may be required to haul trains of various weights, and may also be required

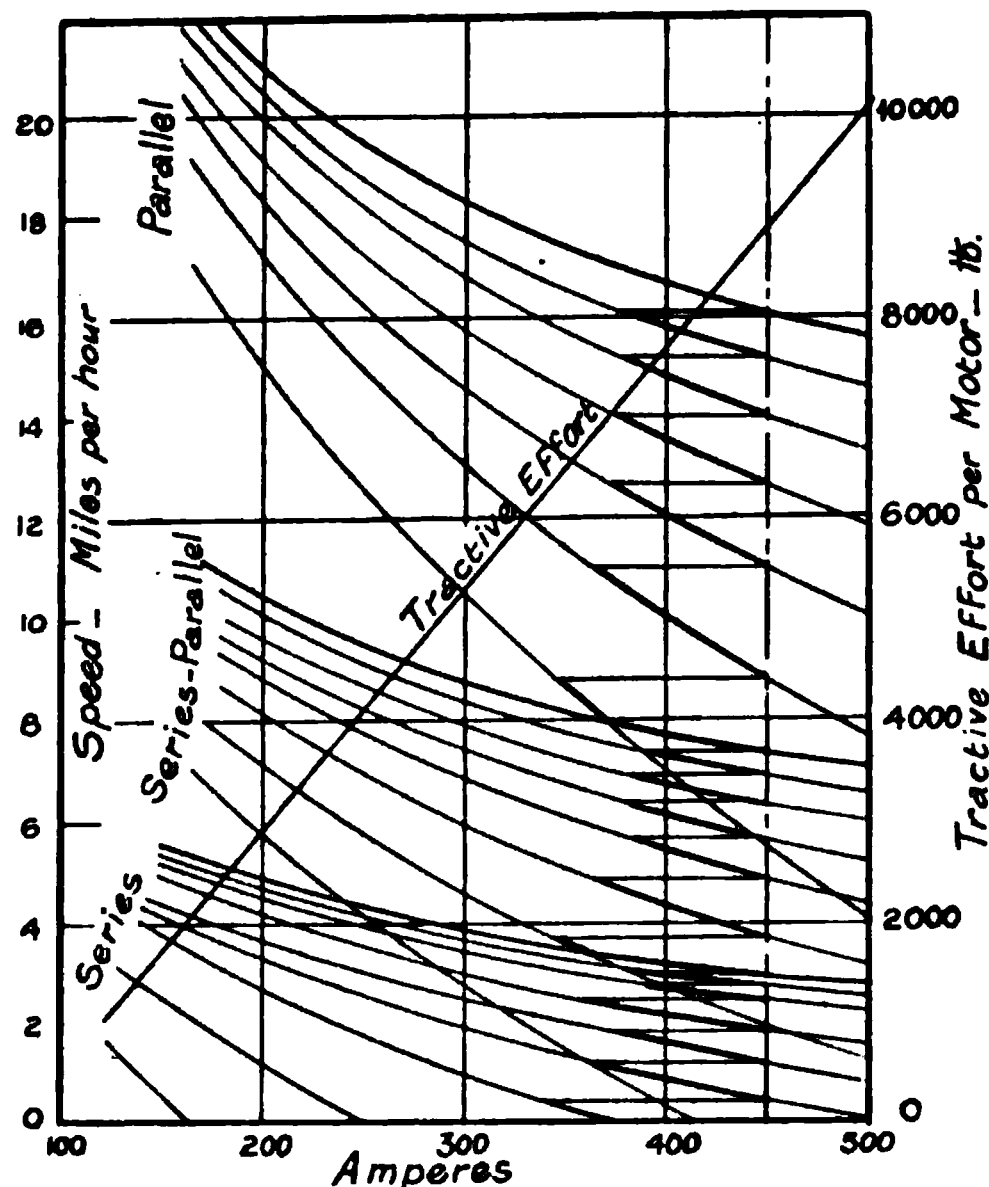


FIG. 173.—Speed Curves—for a Four-motor Locomotive Equipment—corresponding to the various Controller Notches.

to run light. Thus it is obvious that, if the rheostats were adjusted to give the tractive-effort required for accelerating a heavy train, then the accelera-

tion with the locomotive running light would probably be sufficient to unseat the driver. Therefore, to meet these conditions, additional notches and rheostat sections must be provided (see Fig. 173). The gradual application of the tractive-effort and draw-bar pull is essential for the safe handling of freight trains which are made up with slack couplings. The additional rheostat sections must be designed so that the slack can be gradually pulled out of the couplings.

For locomotive service the double-series-parallel system of control possesses advantages over the ordinary series-parallel system: thus (1) a larger number of notches can be provided, (2) three running speeds are available, and (3) the rheostatic losses are lower than those for a corresponding series-parallel system.

In the case of a freight locomotive accelerating a heavy train up a gradient, the tractive-effort required may approach the limiting value at which slipping of the driving wheels occurs. Under these conditions it is imperative that the limiting tractive-effort be not exceeded on any notch, and the controller must be held on a notch until the current has decreased to the minimum value. The rheostats should therefore be proportioned to allow of considerable time being spent on each notch. Thus with control equipments for heavy freight locomotives it is standard practice to instal rheostats having a 5-minute rating, while under exceptionally severe operating conditions continuously-rated rheostats are installed. These equipments form a striking contrast to those for motor-coach trains, in which a 20-second rating for the rheostats is general practice.

CHAPTER X

THE CONTROL OF SINGLE-PHASE RAILWAY MOTORS

THE control of the speed and torque of single-phase railway motors is usually accomplished by the variation of the voltage applied to the motors, but in some cases the control is wholly or partially performed by means of brush shifting.*

With motors of the series-repulsion type provision must also be made for changing the motor connections from repulsion to series, and supplying the armature and exciting windings with various voltages.

The voltage control of alternating-current motors differs from that of continuous-current motors in that rheostats are dispensed with, the various voltages being obtained from a transformer or from an induction regulator. Series-parallel control of the motors is, therefore, unnecessary. Moreover, *each control point becomes a running point*, so that a number of economical speeds are available. This feature is of considerable importance in connection with the control equipments for freight locomotives, and has already been discussed in Chapter IX.

Since all alternating-current railways are supplied at high voltage, a transformer will be required in order to obtain the correct voltage for the motors. Although repulsion motors may be operated at the full supply voltage, it is undesirable, in practice, to employ a high voltage on the stator.† Moreover, a transformer is required, in any case, for supplying the auxiliary machines, lighting, heating, &c. Hence it is the general practice to supply all types of motors from a transformer, whether the control is by brush-shifting or voltage regulation. The secondary winding of the transformer is arranged with tapplings, so that the various voltages for control, lighting, heating, &c., can be obtained.

The normal operating voltages of the various types of motors and auxiliary apparatus are as follows: series motors (moderate output), 250 to 320 volts; series motors (large output), 400 to 500 volts; repulsion motors, 750 to 1000 volts; auxiliary motors for compressors, blowers, &c., 110 to 220 volts; lighting and heating, 110 to 220 volts.

* Repulsion motors of the Déri type are controlled entirely by brush shifting.

This method of control, in conjunction with voltage variation, has also been applied to repulsion motors by the A.E.G., and to series motors by the Bergmann Co. See *The Engineer*, vol. 113, p. 522; vol. 114, p. 11.

† This statement applies to compensated-repulsion and brush-shifting repulsion motors. It may be remarked that the original claims of the compensated-repulsion motor being suitable for high voltages have not been substantiated, as these motors are now wound for about 750 volts.

The regulation of the voltage supplied to the motors may be performed by means of (1) several tapplings on the secondary winding of the transformer, in conjunction with contactors or a controller; (2) an induction regulator* connected between the secondary winding of the transformer and the motors; (3) a combination of (1) and (2).

The first of these methods is largely used in practice, and is similar in principle to the contactor system of controlling continuous-current motors. In the present case, however, the contactors are connected to the various tapplings on the transformer, and it is obvious that, in the closing of the contactors, we must take precautions to avoid the successive short-circuiting of the different sections of the transformer winding. This may be overcome by (a) having only one contactor closed at the same time, (b) connecting a preventive coil† in the circuit between two adjacent contactors, (c) providing double secondary windings (each with suitable tapplings) on the transformer, and arranging the connections so that, under normal conditions, the motors and secondary windings

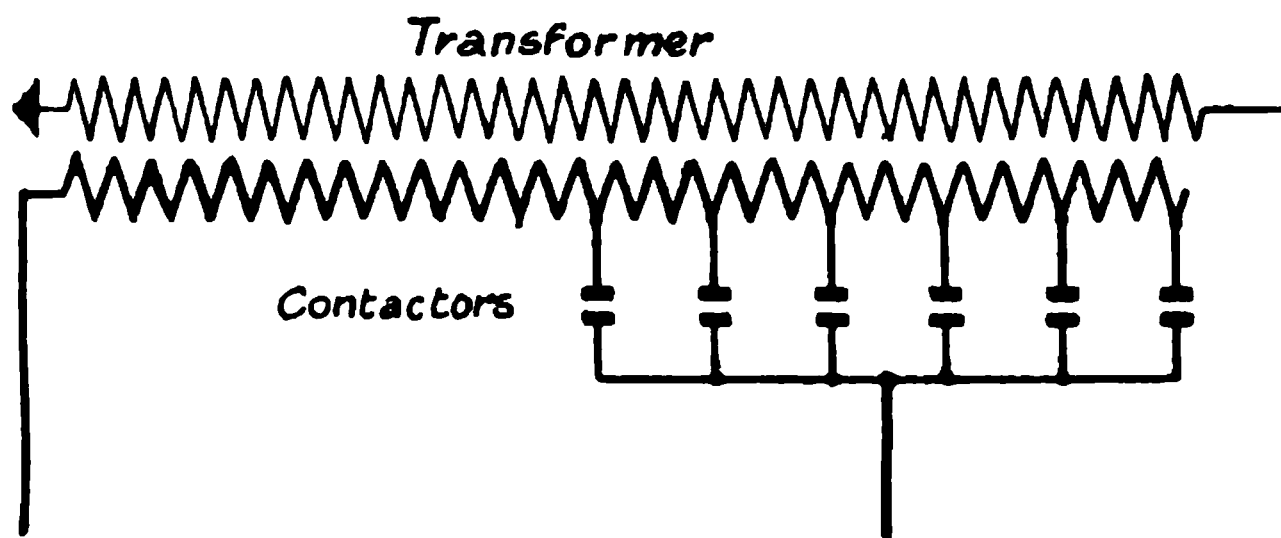


FIG. 174.—Method of Connecting Contactors for Open-circuit Transition.

are in series, but during transition the motors are connected in parallel across one secondary winding.

The first method of transition (a) possesses the merits of simplicity, and enables the control to be effected with a small number of contactors, but it involves opening the motor circuit in passing from notch to notch,

* An induction regulator is a booster-transformer in which one of the windings (usually the primary) is carried on a movable core which can be moved through 180 (magnetic) degrees.

The apparatus (see Fig. 192, p. 222), therefore, resembles an induction motor rather than a static transformer.

The primary winding is excited at constant voltage, and the secondary winding is connected in series with the circuit, the voltage of which is to be regulated. The voltage induced in the secondary winding depends on the relative positions of the primary and secondary windings, and can be varied gradually (by rotating the movable core carrying the primary winding) from a negative maximum value to a positive maximum value.

† A preventive coil consists of a laminated magnetic circuit wound with a single winding which is tapped at the centre point. Such a coil will offer a high impedance to an alternating current passing through the winding from end to end, but will exert practically no choking effect upon an alternating current passing between the centre point of the winding and the two ends, since, in the latter case, the resultant ampere-turns are zero.

If the winding be connected between adjacent tapplings of the transformer the potential of the centre point will be midway between that of the tapplings, since, under these conditions, the preventive coil is virtually an auto-transformer with a ratio of 2 : 1.

thereby producing jerky acceleration and arcing at the switch contacts. The connections are shown diagrammatically in Fig. 174.

The **second method of transition (b)**—the connections for which are shown diagrammatically in Fig. 175—requires the contactors (1, 2 . . . 6) to be arranged in two groups (viz. 1, 3, 5; 2, 4, 6), with the common terminals *A*, *B* of each group connected to a preventive coil *C*,* the connection to the motor being taken from the centre-point of the coil.

In this method two contactors, connected to adjacent tapings, are closed on each running notch, and the motor is supplied through the preventive coil at a voltage approximately midway between that of the tapings to which the preventive coil is connected. Each contactor, therefore, only carries approximately one-half of the motor current. In transition, one contactor is opened and another contactor of the same group is closed. Thus, suppose the motor is being supplied from con-

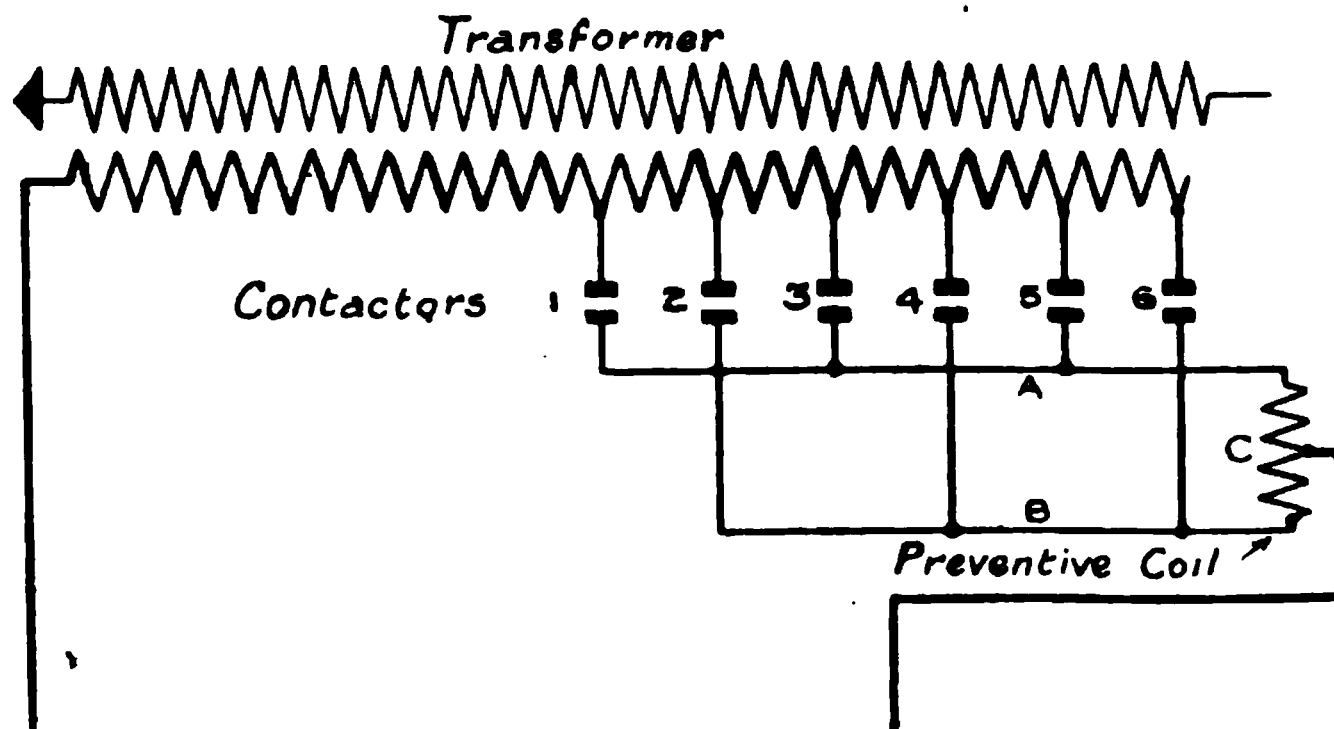


FIG. 175.—Method of Connecting Contactors for Closed-circuit Transition.

tactors 3 and 4: to increase the voltage, contactor 3 is opened and 5 is closed; while, to decrease the voltage, contactor 4 is opened and 2 is closed.

During the transition period the full motor current is carried by one contactor and one-half of the preventive coil, but, as the transition period is of very short duration, a contactor rated (continuously) at one-half of the motor current would be able to carry this current without overheating.

Of far greater importance, however, is the **division of current in the preventive coil**, and the manner in which this coil affects the motor voltage.

Under normal conditions the currents in each half of the coil and the sections of the transformer are distributed in the manner shown in Fig. 176, the difference between the currents in the two portions of the coil being equal to twice the normal magnetising current. The coil, therefore, exerts practically no choking effect upon the motor current.

The conditions, however, are very different when one-half of the coil carries the whole of the motor current. In this case a considerable

* A resistance may also be used, but this requires to be short-circuited after the transition has been effected. Moreover, in this case, only one of the contactors (1-6) must be closed on each running notch.

choking effect will be produced unless the magnetic circuit of the coil is designed with a high reluctance. Hence it will be desirable to design the preventive coil with a moderately large magnetising current. This will, of course, affect the division of current in the two portions of the coil, while the phase of the motor voltage will also be slightly affected.

The phase relations between the currents and voltages in the two portions of the preventive coil and the transformer are shown in the

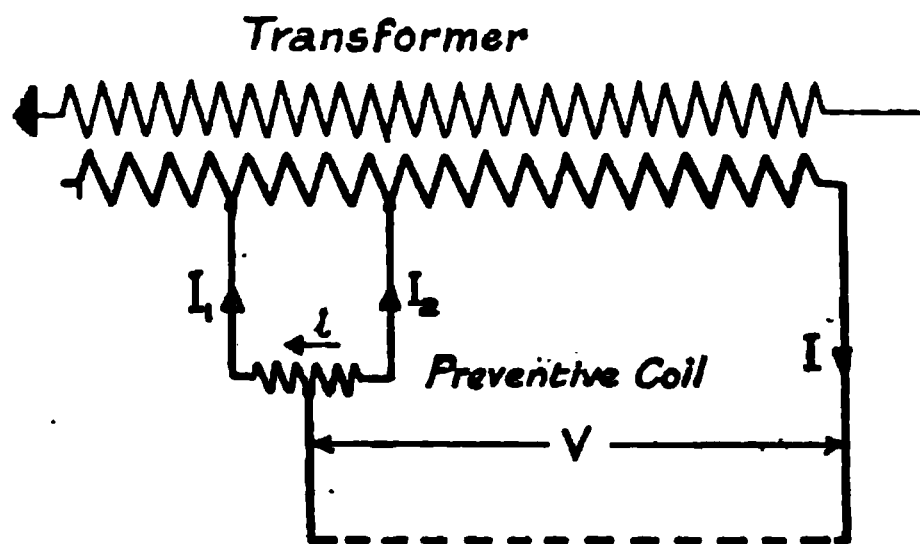


FIG. 176.

vector diagram of Fig. 177, which refers to the circuit diagram of Fig. 176. In Fig. 177, OE represents the voltage of the transformer, OI the (lagging) motor current (I), and Oi the magnetising current (i) of the preventive coil. The currents in the two portions of the preventive coil must differ by $2i$: they are therefore represented by OI_1 and OI_2 .

To obtain the motor voltage we must subtract the voltage

drop in the left-hand portion of the preventive coil (Fig. 176) from the voltage of the transformer. Oa (Fig. 177) represents the induced voltage in this portion of the preventive coil, Ob the voltage drop due to resistance, and Oc —the resultant of Oa and Ob —the total voltage drop. The motor voltage is given by OV , the resultant of OE and Oc .

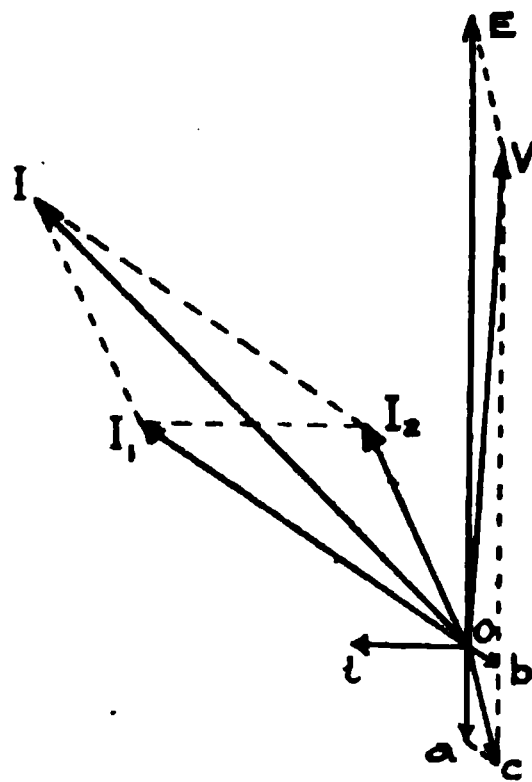


FIG. 177.

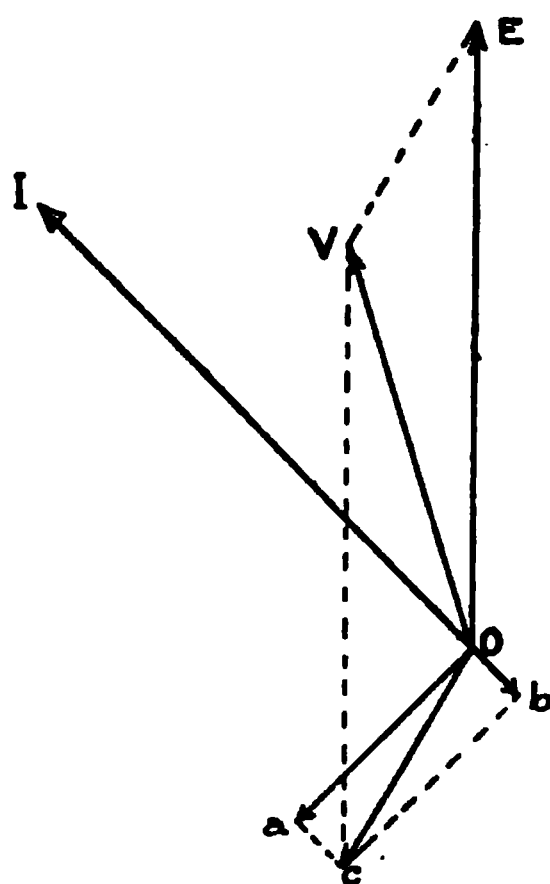


FIG. 177a.

Vector Diagrams showing the effect of Preventive Coil on Motor Voltage.

If the motor current be now passed through the left-hand portion of the preventive coil, the induced voltage in the coil will be $(I/i \times \frac{1}{2}Oa)$, neglecting saturation. The phase of this E.M.F. will be 90 degrees from the current I , and the E.M.F. is, therefore, represented in Fig. 177a by Oa . Hence the motor voltage will be given by OV , which is obtained

in the same manner as in the previous case. It is apparent that the smaller the ratio I/i , the less will be the disturbing effect on the motor voltage during the transition period.

The above method of control may be extended as shown in Fig. 178,* where the motor current is now divided between four contactors. These connections, however, require the use of a large number of contactors; but, for controlling large motors, the method has the advantage that the current to be carried by each contactor is only one-quarter of the main current. Moreover, a large number of voltages are available, so that smooth acceleration can be obtained.

In the **third method (c) of transition**† (which requires double secondary windings on the transformer and two groups of contactors)

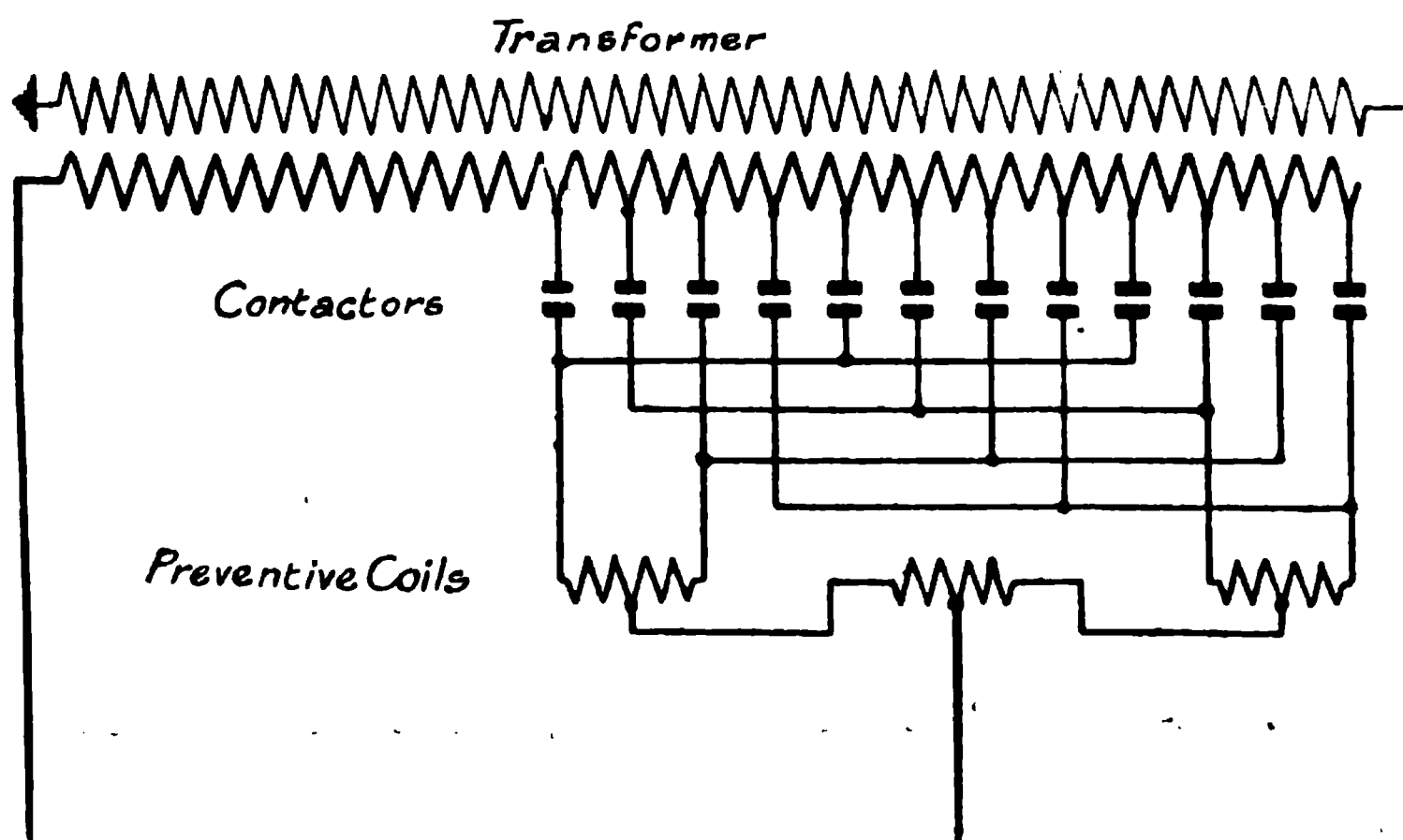


FIG. 178.—Method of Connecting Contactors for Closed-circuit Transition when a large number of speeds are required.

the motors must be connected in two groups—i.e. the equivalent of two motors—and each secondary winding must be designed for the full voltage of each group of motors.

The connections are shown diagrammatically in Fig. 179. Under normal running conditions two contactors—one of each group—are closed, so that the motors and transformer windings form a closed series circuit. The tappings on the two secondary windings, however, are arranged to give unequal voltages, and the voltage on the motors is equalised by the two cross-connected preventive coils which are wound on a common core so that they can act inductively upon each other.

The transition from one tapping to the next is effected by opening a contactor and closing one of the contactors adjacent to it. Thus, suppose contactors 3 and 4 are closed; to increase the voltage, contactor 3 is opened and 5 is closed; while to decrease the voltage, contactor 3 is opened and 1 is closed.

* This method of control has been standardised by the Westinghouse Co. for the control equipments of single-phase locomotives.

† Developed by Messrs. Siemens-Schuckert.

During the transition period (when only one contactor is closed) both motors are supplied from one secondary winding, the motors being in parallel with a preventive coil in series with each. As the preventive coils are both wound on the same core, the resultant ampere-turns will be zero if the motors are equally loaded, so that these coils do not exert any choking effect. If the currents in the motors are unequal, the preventive coils will tend to equalise these currents.

Although we have assumed contactors to be used for effecting the combinations between the motors and the transformer, a **drum-type controller** can be adapted to perform the same operations. A system (described on p. 220), in which a mechanically-operated controller is used, has been developed by the Oerlikon Co. for motors up to 1250 H.P.,

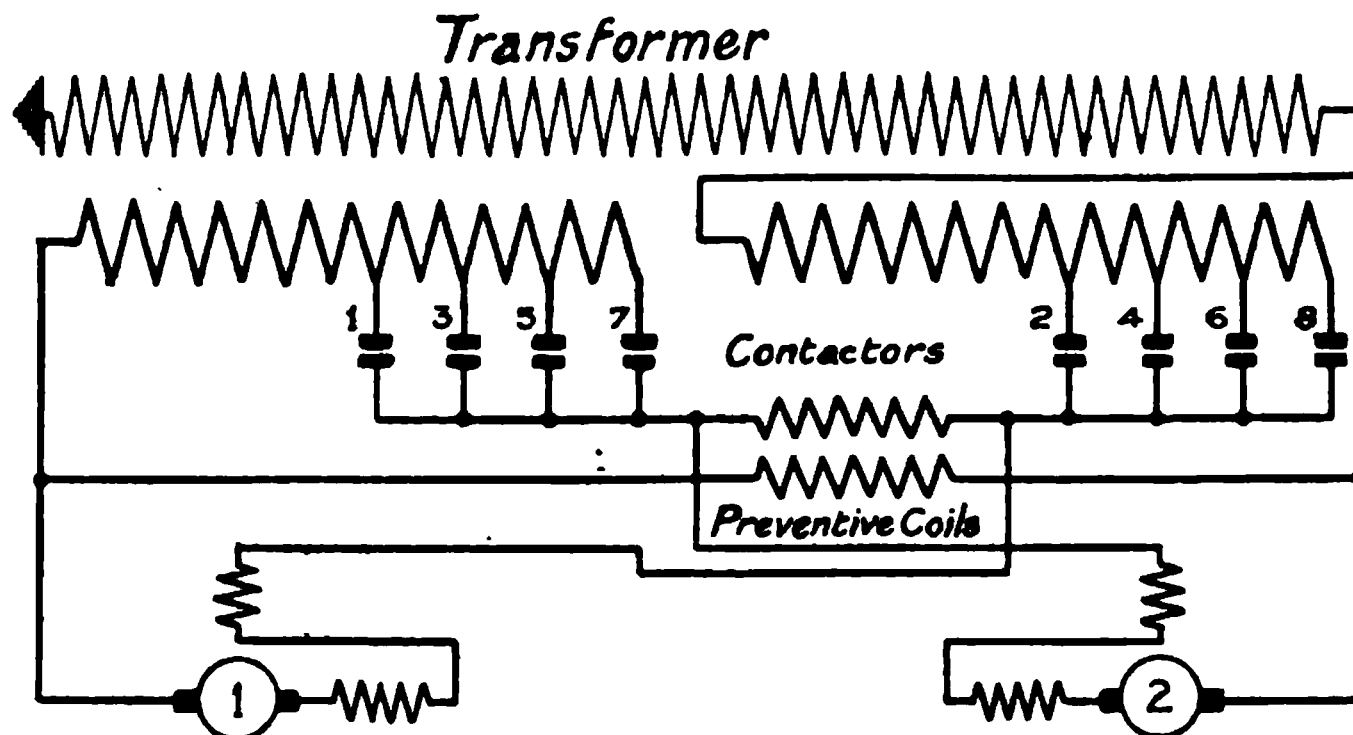


FIG. 179.—Siemens' Method of Connecting Contactors for Closed-circuit Transition.

and, notwithstanding the large currents to be handled, the maintenance cost of the controller is claimed to be lower than that of contactors.

With the **induction regulator method of control**—which is shown diagrammatically in Fig. 180—it is not necessary to provide tappings on the transformer unless these are required for lighting, &c.

The voltage of the transformer secondary, however, must be lower than that of the motor by an amount equal to the voltage of the secondary winding of the induction regulator. Thus, if the normal voltage of the motor is 300 volts, and a voltage of 100 volts is required for starting, then the induction-regulator secondary must be rated at 100 volts and the transformer voltage must be 200 volts. In the maximum negative boost position of the regulator—where the secondary voltage is in opposition to the supply voltage—the motor voltage will be 100 volts, which can be increased gradually to 300 volts by moving the regulator into the position of maximum boost.

The induction regulator method of control, therefore, possesses important advantages over the contactor method, these advantages being (1) the elimination of contactors and their maintenance, (2) no tappings required on the transformer for purposes of control, (3) a fine gradation of the voltage applied to the motor, so that a perfectly uniform torque can be obtained throughout the accelerating period.

On the other hand, an induction regulator for a large motor is a costly and heavy piece of apparatus, occupying considerable space. Moreover, the regulator usually requires to be operated by a motor, while it is not without complication* when automatic or semi-automatic control is desired.

On account of the air-gap between the primary and secondary members of the regulator, the magnetising current will generally be comparable with that of an induction motor of similar rating. This magnetising current has, of course, to be supplied by the transformer, so that, as a general result, the power-factor of a system in which the induction regulator method of control is adopted will be lower than that of a similar system in which the control is on the contactor method.

Combination of Induction Regulator and Contactors.—The objections to the induction regulator method of control can be greatly

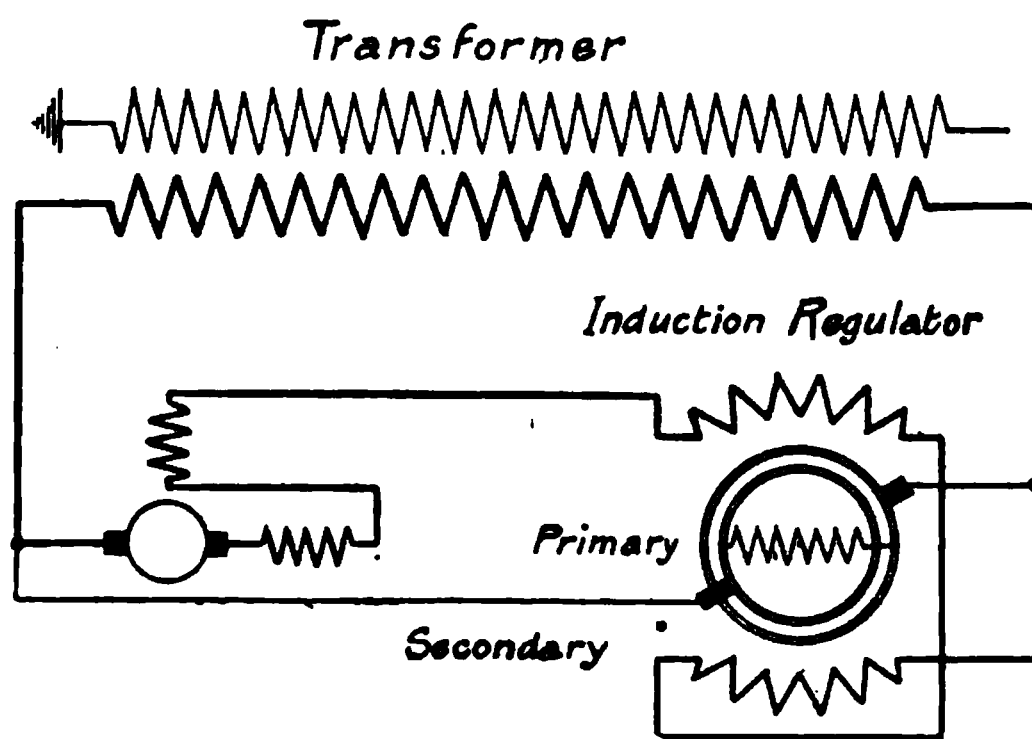


FIG. 180.—Diagram of Induction-regulator Method of Control.

minimised by combining an induction regulator with a group of contactors.† In this combined system it is possible to obtain the same gradation in the voltage applied to the motors as in the induction regulator system, although the induction regulator, in the present case, is only of small size.‡ Moreover, the number of contactors may be lower than that required for plain contactor control, but, as the number of contactors is reduced, the size of the regulator is increased.

The general features of this system are represented diagrammatically in Fig. 181. If this diagram be compared with that in Fig. 175, it will be observed that the method of grouping the contactors is the same

* In this connection see *The Electric Journal*, vol. 10, p. 995, article by R. E. Hellmund on "Electrification of Trunk Lines in Europe."

† See paper on "Control Equipments for Electric Locomotives," by F. Lydall, *Journal of the Institution of Electrical Engineers*, vol. 52, p. 390.

‡ If the voltage between theappings of the transformer is v , the volt-ampere rating of the regulator will be $\frac{1}{2}vI$, where I is the motor current.

The volt-ampere rating of a regulator, when no contactors are used, will be $\frac{1}{2}VI$, where V is the maximum variation of the voltage required.

Hence, if a variation of 200 volts is required, the rating of the regulator (when no contactors are used) will be $100I$; whereas, if the transformer is provided with 25-voltappings and contactors, the rating of the regulator will be only $12.5I$, or one-eighth of that required when no contactors are used.

in the two cases, and that the preventive coil in Fig. 175 is replaced, in Fig. 181, by the secondary winding of the induction regulator.

The regulator is designed so that, when its primary winding is excited from the terminals of the transformer, the secondary winding will give a voltage equal to that between adjacent tapings.

Hence if, say, contactor 2 is closed and the regulator is in the position of maximum positive boost, there will be no voltage across contactor 3. Similarly, if the regulator is in the position of maximum negative boost, there will be no voltage across contactor 1.

The motor voltage in the two cases will be approximately equal to $V + \frac{1}{2}v$ and $V - \frac{1}{2}v$ respectively, V being the voltage between terminal T and tapping 2, and v the voltage between the tapings.

The above positions of the regulator correspond respectively to the transition points from contactors 2 to 3 and from contactors 2 to 1.

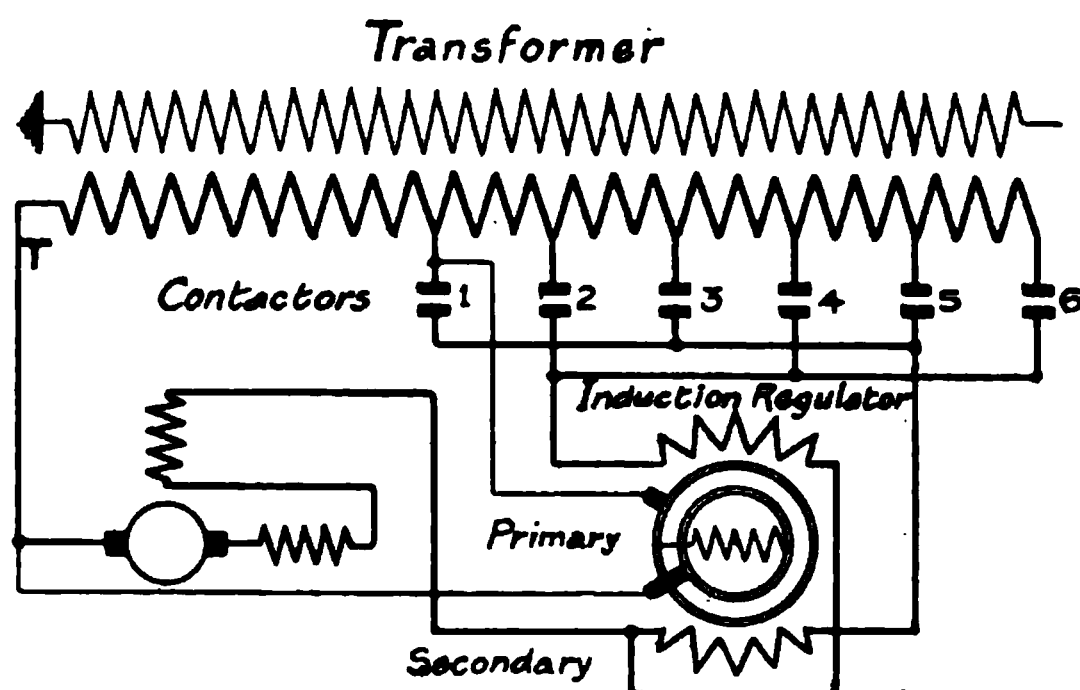


FIG. 181.—Diagram of Combined Induction-regulator and Contactor Method of Control.

During transition two contactors are closed and the motor current is divided approximately equally between them. On opening one contactor, only one-half of the motor current has to be broken at a very low voltage.

In practice the movable member of the induction regulator is arranged so that it can be rotated in either direction, and the transition is effected automatically by means of a small drum controller operated from the movable member of the regulator by suitable gearing.*

CONTROL APPARATUS FOR SINGLE-PHASE EQUIPMENTS

Of the methods of voltage control discussed above, the method in which contactors are used in conjunction with tapings on the transformer is obviously better suited for multiple-unit motor-coaches than the methods involving the use of an induction regulator. For locomotives, however, all the above three systems are available, but, as a result of extensive tests with each system on the Continent, the general tendency is towards the exclusive use of contactor control.† Moreover,

* For diagrams showing the connections of this controller, see *The Engineer*, vol. 113, p. 440; *Journal of the Institution of Electrical Engineers*, vol. 52, p. 394.

† *Ibid.*, p. 396. See also *The Electric Journal*, vol. 10, p. 985.

the contactor system of control has been standardised in America for all single-phase equipments, while it is used on all the single-phase equipments in this country—viz. the London, Brighton, and South Coast Railway and the Midland Railway (Lancaster-Heysham branch).

It will therefore be desirable to consider in what respects the apparatus for this (contactor) system of control differs from that for continuous-current equipments.

The general principle is the same in each case—i.e. the contactors are operated electrically (or electro-pneumatically) from a master controller, and the current for the control circuit is obtained from either the main transformer, an auxiliary transformer, a storage battery, or a small motor-generator set.

In the two latter cases the contactors are operated with continuous current, and do not present any special features.

On the other hand, a contactor designed for alternate-current operation possesses features which are not found in a contactor designed entirely for continuous-current operation. Thus the magnetic circuit

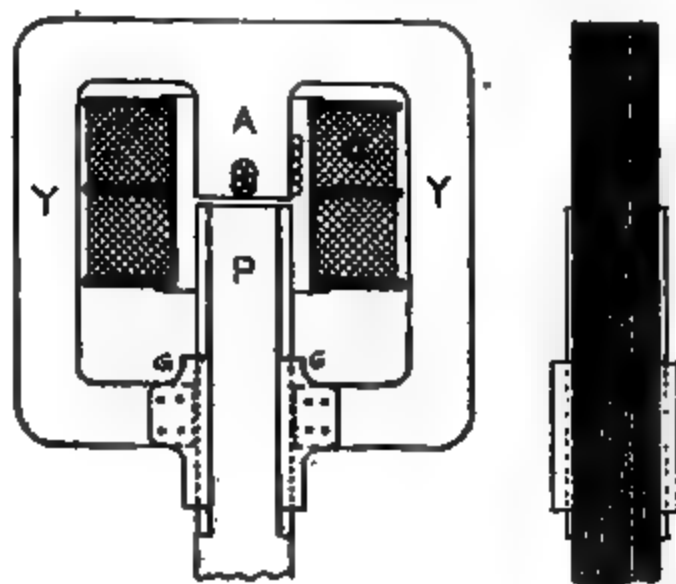


FIG. 182.—Magnetic Circuit of Single-phase Contactor.

must be laminated and must be provided with yokes in order to reduce the ampere-turns required in the operating coil, while provision must be made to avoid the chattering, or vibration, of the plunger due to the pulsating flux. Moreover, on account of the low voltage of alternating-current series motors, the main contacts of the contactors may have to carry very large currents. Therefore, if a strong blow-out field has to be provided, precautions must be taken to avoid the generation of eddy currents in the main contacts.

The type of magnetic circuit generally adopted for an alternating-current railway contactor is shown in Fig. 182. In this diagram, *P* represents the laminated plunger—of rectangular cross-section—working in the brass guides, *G*, *C* the operating coil, *A* the pole core, and *Y* the yoke. Chattering

FIG. 183.—Siemens' Contactor.
A, main contacts; *B*, *C*, coil and yoke of blow-out; *D*, operating coil; *E*, resistance for "shading" coil; *F*, arc chute.

of the plunger is prevented by means of a short-circuited coil (called a "shading" coil) inserted in the face of either the plunger or the pole-piece. This coil may consist of a solid band of copper or of several turns of wire connected to a resistance, but in either case the coil must only embrace a portion of the pole face, as indicated in Fig. 182. The "shading" coil produces an irregular two-

phase magnetic field at the pole face, and, in consequence, the pull is practically steady.*

In some cases, however, a steady pull is obtained by providing two operating coils and supplying these coils with currents differing in phase.

A characteristic feature of all alternating-current contactors is the automatic reduction of the current in the operating coil (assuming this coil to be connected to a constant voltage) as the plunger is pulled up. It is apparent that, when the operating coil is connected to an alternating-current circuit of constant voltage, the flux in the core must remain constant (except for variations in the resistance drop and leakage), irrespective of the position of the plunger.

Now the ampere-turns required to produce this flux are proportional to the reluctance of the magnetic circuit. The maximum reluctance occurs when the plunger is in the position corresponding to the main contacts being fully open; the minimum reluctance occurs when the

FIG. 184.—Group of Siemens' Contactors. (Rear view showing interlocking levers.)

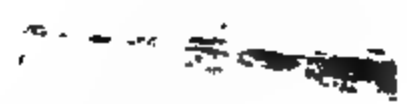
plunger is pulled up (i.e. when the main contacts are fully closed). The ratio of the maximum and minimum currents will, therefore, depend upon the stroke of the plunger, and may be of the order of 5 to 1, according to the design.

In order to obtain a quick release of the plunger at the cessation of the operating current, the pole face of the plunger should not come into contact with the pole face of the core, and the plunger should be moderately heavy. In some types of contactors, in which the plungers are relatively light, a demagnetising coil is provided for the purpose of obtaining a quick release of the plunger, this coil being supplied with current out of phase with the operating current.

The various contactors connected with the control system must be interlocked to prevent the short-circuiting of the transformer tapplings due to incorrect closing or sticking of the contactors. This **interlocking** is generally accomplished electrically, by means of auxiliary contacts (similar to those on continuous-current contactors), but with one type of contactor the interlocking is accomplished by mechanical means.

* An interesting series of tests on a single-phase contactor of this type is given in *The Electrician*, vol. 70, p. 1130. The tests include an investigation of the effect, on the pull of inserting inductance and capacity in series with the "shading" coil. The results indicate that no improvement in the pull can be produced by these means.

FIG. 185.—Group of Westinghouse Contactors for Motor-coach Service.



**FIG. 186.—A.E.G. Contactor Group and Reverser in position on Motor Coach
(London, Brighton, and South Coast Railway).**

Examples of contactors in use on alternating-current single-phase railways are illustrated in Figs. 183 to 186.

The Siemens' contactor (Fig. 183) is designed with duplicate contacts having a horizontal motion (instead of a vertical motion as in other contactors). One pair of contacts, located in an arc chute, is provided

FIG. 187.—Oerlikon Electrically-operated Controller.

with a magnetic blow-out and is arranged to close before and to open after the other pair of contacts. All arcing, therefore, occurs at the former contacts. Provision is also made for short-circuiting the blow-out coils when the contactor is fully closed.

The contactors (or unit switches) of the Westinghouse Co. are of the same general design as those described in Chapter IX.

On motor-coaches the contactors are generally located in special

Fig. 188. Oerlikon Electrically-operated Controller in position on Transformer. **Fig. 189.**

boxes fixed to the underframe of the coach, but on locomotives the contactors are usually arranged on a framework in a special compartment. Figs. 184, 185, 186 show typical examples of contactor groups.

The **Oerlikon electrically-operated controller** is illustrated in Fig. 187. The controller is mounted on the top of the transformer, and the tapings are connected directly to the fingers of the main cylinder (see Fig. 188), thereby simplifying the connections, and avoiding the carrying of heavy conductors from the transformer to the control gear. The latter point is of considerable importance in large locomotives, where the current per motor (with series machines) may reach 3000 amperes.

The main cylinder is moved to the respective notches by means of

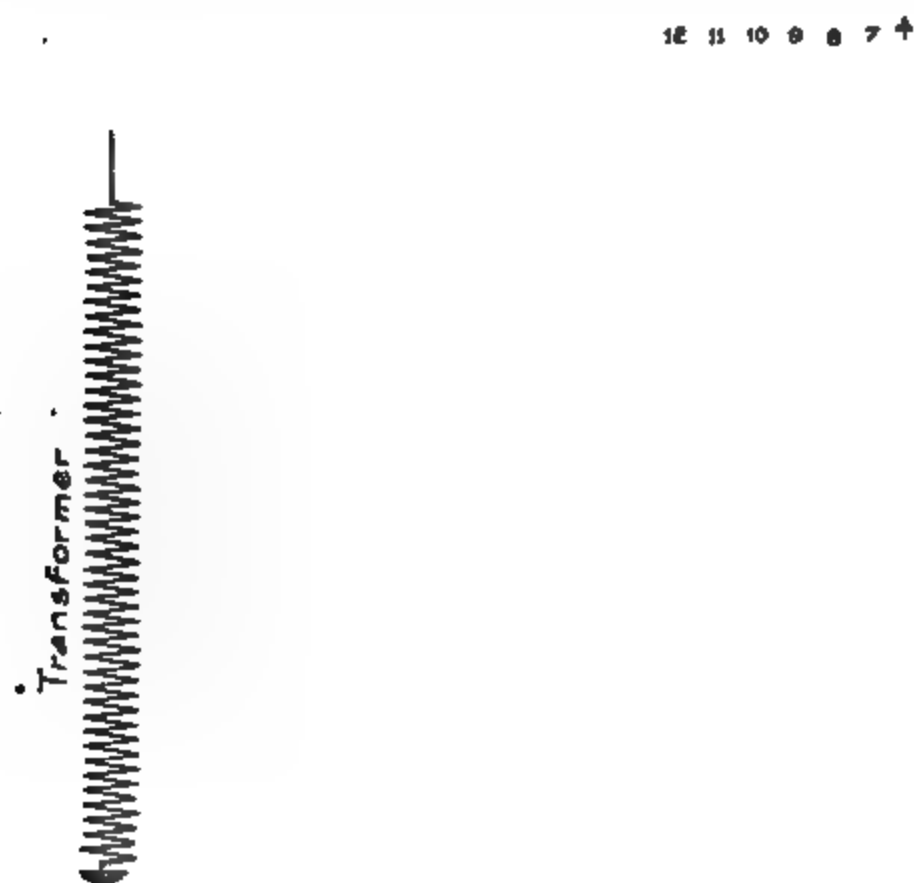


FIG. 190.—Connections and Development of Oerlikon Electrically-operated Controller.

a small continuous-current motor, in conjunction with a ratchet-wheel and two electrically operated pawls. The ratchet-wheel is fixed to the controller shaft, while the arm carrying the pawls is free on this shaft, and is maintained in a state of oscillation (through a definite arc) by means of a slotted connecting-rod and a crank, the latter being worm-driven from the motor. The pawls are operated by electro-magnets which are energised from the master controller, one pawl being used for moving the cylinder in one direction, and the other pawl for returning the cylinder to the "off" position. Suitable interlocks ensure that the cylinder takes up a position corresponding to the particular position of the master controller.

The tapings of the transformer are connected to fingers, which are arranged in two equal groups, one group on each side of the main cylinder, as shown in the connection and development diagram of Fig. 190. Two other fingers, *X*, *Y*, are connected to the preventive coil

A, B , and another pair of fingers, W, V , are connected to two mechanically operated contactors C_1, C_2 (which are provided with magnetic blow-out), at which the main circuits are made and broken. The contactors C_1, C_2 are separate from the controller cylinder, and can be seen in the view of the controller in Fig. 189. They are actuated by a mechanical device (which is geared to the main cylinder), so that the correct contactor operates in passing from notch to notch.

The manner in which all the arcing is confined to the contactors is shown more clearly in the elementary diagram of Fig. 191. In this diagram the fingers 1, 2, 3, 4 are connected to the respective tappings on the transformer, while fingers D, H and F, K are connected respectively to the ends A, B of the preventive coil, the centre point of which is connected to the motor. The contactors are represented by C_1, C_2 ;

Transformer



FIG. 191.—Elementary Diagram of principle of Oerlikon Controller.

they are connected respectively to the fingers E, J and G, L . When the main cylinder is moved to the first notch, the segment M makes contact first with fingers 1 and E . The contactor C_1 is then closed, and is finally short-circuited when the segment makes contact with finger D .

A similar process takes place in passing to the second notch, on which the other end, B , of the preventive coil is connected to tapping 2.

In the transition to the third notch, segment M first breaks contact with finger D , thereby removing the short-circuit on contactor C_1 (which now carries approximately one-half of the motor current). This contactor is then opened, and segment M breaks contact with fingers E and 1. Connection is now made between fingers 3 and J by segment O ; contactor C_2 is closed, and is finally short-circuited by finger H .

In the actual controller (Fig. 187) the number of fingers is considerably less than the number shown in the elementary diagram of Fig. 191, as, by a suitable arrangement of segments, it is possible to replace fingers D, H , &c.; F, K , &c.; E, J , &c.; G, L , &c., by four fingers (lettered X, Y, V, W in Fig. 190).

Controllers of the type illustrated in Fig. 187 have been standardised by the Oerlikon Co. for all single-phase locomotives above 500 H.P.

If the connection-development diagram (Fig. 190) of this controller be compared with the connection diagram (Fig. 175) for the contactor method of control, it will be found that the method of transition is the same in each case, and that the controller performs functions similar to those of the contactor group.

Induction Regulators.—The advantages and disadvantages of the induction regulator method of control have already been discussed. We have also stated that this method of control has, to some extent, been displaced by the contactor method, on account of certain features

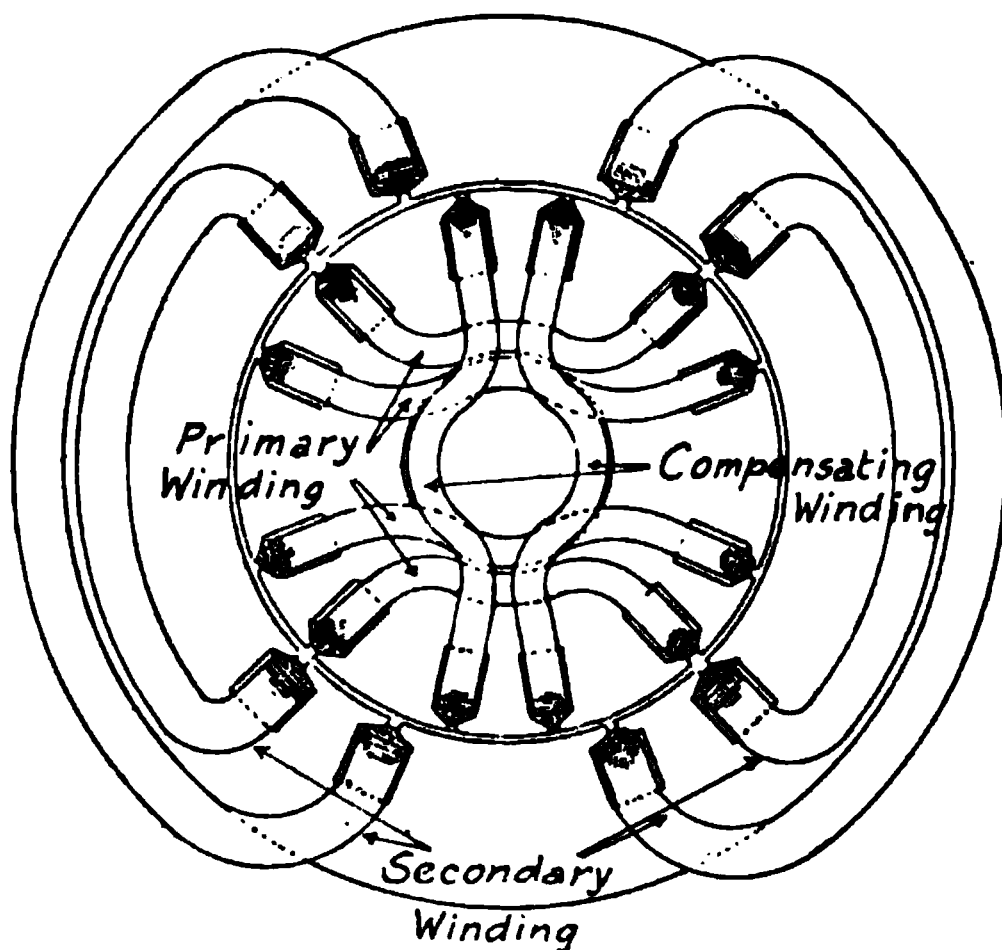


FIG. 192.—Diagram of the Primary, Secondary, and Compensating Windings on a Single-phase Induction Regulator.

of the induction regulator when used on low-frequency single-phase systems.

In all single-phase induction regulators the flux is alternating in character, and has a fixed direction relative to the primary winding. When the rotor is in the neutral (or "no boost") position, the conductors of the secondary winding are situated in the path of the flux produced by the primary winding; consequently, due to the interaction of the primary flux and the secondary current, the rotor will be subjected to a torque. This torque will be pulsating in character, thereby causing excessive vibration, and may reach very high values in a regulator for a large motor, especially when the latter is heavily loaded or short-circuited (due to slipping of the driving wheels).

It is apparent, therefore, that the mechanical parts of the regulator must be exceptionally strong, while for moving the rotor a motor of several horse-power will be required.

All single-phase induction regulators must be provided with a **compensating winding** on the same member as the primary winding, the axis of the former being at right angles to that of the latter (see Fig. 192).

The compensating winding is usually of the short-circuited type, and neutralises the ampere-turns of the secondary winding when the rotor is in the neutral position, thereby reducing the reactance of this winding.* In other positions of the rotor, the secondary ampere-turns are neutralised partly by the ampere-turns of the primary winding and partly by the ampere-turns of the compensating winding, so that the voltage drop in the secondary winding, for a given secondary current, is practically constant for all positions of the rotor.

As an example of a single-phase induction regulator applied to railway service, we may consider the combined regulator and trans-

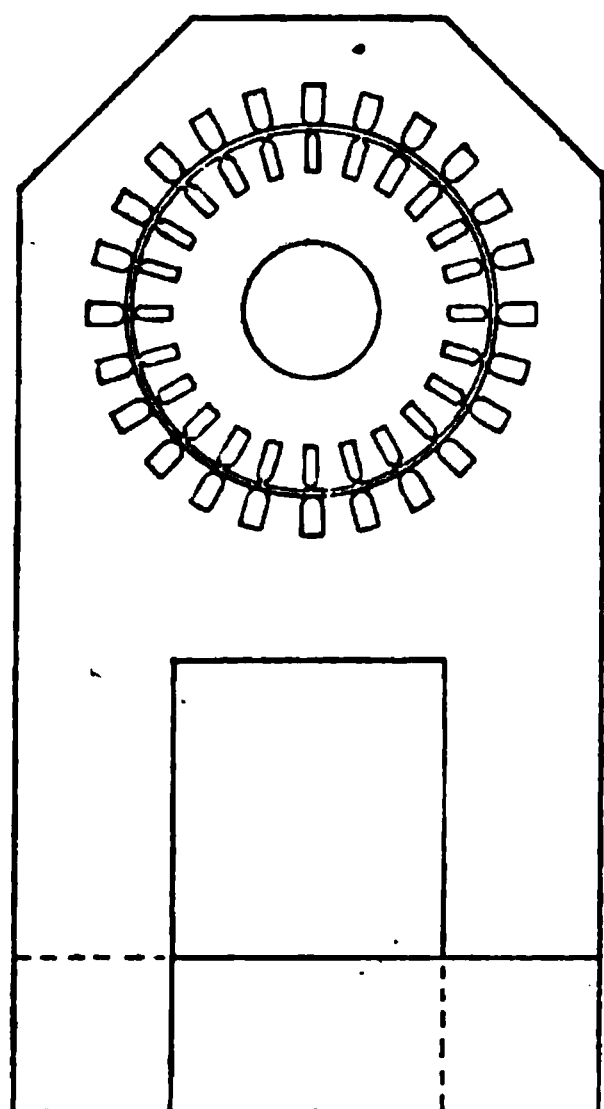


FIG. 193.

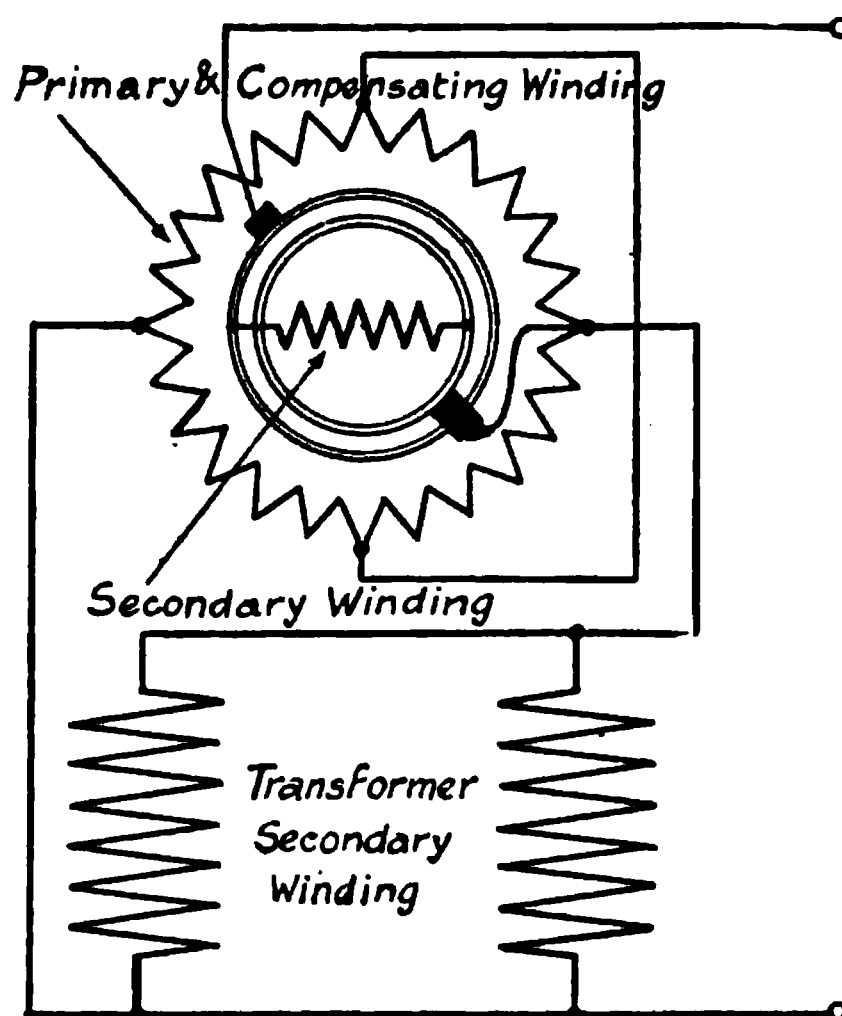


FIG. 194.

Magnetic Circuit and Connections of "Jeumont" combined Transformer and Induction Regulator.

former developed by the Ateliers de Constructions Électriques du Nord et de l'Est (known as the "Jeumont Co.") for the electric locomotives supplied by this firm to the Midi Railway.

The regulator is of the two-pole type, and its magnetic circuit forms part of the magnetic circuit of the transformer.† In this manner a compact device has been obtained, while the combination of the transformer and regulator also effects a considerable saving in cost and weight over the usual arrangement of a separate transformer and regulator. The arrangement of the windings and magnetic circuits are shown diagrammatically in Figs. 193, 194.

With the combined regulator and transformer, the primary winding

* Without the compensating winding, the secondary ampere-turns would be expended in saturating the magnetic circuit, and would thereby produce a large (lagging) counter-E.M.F. in the secondary circuit.

† The regulator is rated at 245 kVA (1750 amps., 140 volts), and the transformer is rated at 450 kVA, 240 volts.

of the regulator must be placed on the stator, and the slip-rings must be designed to carry the full secondary current (which is 1750 amperes in the regulator under consideration).

The primary winding of the regulator is of the distributed type, and is short-circuited across a diameter perpendicular to the magnetic axis (see Fig. 194), so that it forms a compensating as well as an exciting winding.*

The position of the rotor is regulated by means of a repulsion motor located on the top of the transformer. This motor is geared to the rotor by two sets of worm gearing, the total reduction being 1023 : 1. The direction of rotation of the motor is controlled from the master controller in conjunction with limit switches, the latter taking the form of a small drum controller which is chain-driven from the shaft of the rotor of the regulator.

Reversers.—All types of series, compensated-repulsion, and doubly-fed motors require reversing switches to enable the direction of rotation

FIG. 195.—Oerlikon Electrically-operated Reverser.

of the motor to be reversed.† These switches, in general, have to perform the same functions as the reversing switches in continuous-current equipments, but, with the Siemens-Schuckert series motor (in which two excitation windings are provided, one for each direction of rotation) no reversal of the connections is required. In this case the reverser has to connect either the one or the other exciting winding in circuit, and for this purpose two contactors may be used.

In other cases the reverser may consist of a group of four contactors, or of a throw-over drum-type switch with four fingers and two sets of interconnected segments. An illustration of a reverser of the latter type is shown in Fig. 195. This reversing switch controls two 1250-H.P. Oerlikon series motors, and is operated by two solenoids, which are supplied with continuous current.

The **master controllers** are, in general, similar to those for continuous-current multiple-unit control systems, except that, for alternating-current operation, no transition notches are required, and, on

* Compare with the compensated-repulsion motor, in which the armature winding fulfils similar functions (p. 72).

† Reversing switches are not required with the Déri brush-shifting repulsion motor, as the direction of rotation is reversed by reversing the direction of movement of the movable brushes.

account of the low voltage of the control circuit, it is not necessary to provide blow-out coils.

Illustrations of **Westinghouse** master controllers for hand and auto-

**FIG. 196.—Westinghouse Master Controller for Locomotive Service
(Non-automatic Control).**

matic control are shown in Figs. 196, 197, the control circuit in each case being supplied with continuous current at low voltage.

The switch group operated by the controller of Fig. 197 is illustrated in Fig. 185 (p. 217).

The **Oerlikon** master controller (for electric locomotives) is shown in Fig. 198. The central large handle and cylinder controls the motor-operated drum-controllers (of the type illustrated in Fig. 187); the handle to the right of this cylinder controls an electrically-operated reverser (of the type illustrated in Fig. 195); the spindle to the left (without a handle) controls the bow collectors and the control circuit; while the two handles on the extreme left control the high-tension and low-tension oil-switches (which are electrically operated).

For the control of doubly-fed motors a master controller with two cylinders and handles is generally used. One cylinder controls the voltage applied to the terminals of the motor during starting and running, while the other cylinder controls (a) the reverser, (b) the contactor for short-circuiting the armature (to give "repulsion" connections), and (c) the voltage applied to the compensating winding.

The control of brush-shifting motors, of the *Déri* type, has not been developed, at the present time, for multiple-unit operation, and the movement of the brushes is carried out directly from the controller through suitable gearing. The controller, therefore, takes the form of a handwheel with the necessary gearing for transmitting the motion to the brush gear of the motor.

In addition to the handwheel a second handle, with two positions, is usually provided for operating the switch for the stator circuit. This switch is usually operated by compressed air, and the handle controlling the operating valves of the air cylinders is interlocked with the handwheel controlling the brushes, so that the former can only be operated when the angle of displacement of the brushes is zero.

FIG. 197.—Westinghouse Master Controller for Automatic Control (electro-pneumatic system).

Transformers.—For the main transformer a single winding or a double winding may be used; but, as the economy of a single winding (auto-transformer) is only apparent for low ratios of transformation, it is general practice to instal a transformer with a double winding, since this avoids the necessity of earthing one side of the motors.

The transformers for use on motor-coaches are usually of the oil-cooled type. On some equipments, where the motors are of the forced-ventilated type, an air-blast transformer has been installed, with a consequent saving in weight, as, with a transformer of 200 kVA, the weight of the oil is of the order of 500 to 600 lb., and therefore the containing case will be much heavier than the case of an air-blast transformer. On electric locomotives it is the general practice to instal air-cooled transformers.

Protective apparatus.—The transformers and motors are protected against overload by means of automatic overload oil-switches,* while high-frequency lightning discharges are prevented from reaching the transformer by means of some form of lightning arrester and choke coil.

On some electric locomotives—where a single transformer supplies the motors and all the auxiliary circuits—an automatic overload oil-switch is inserted in the motor circuit in order that an overload on the motors

FIG. 198.—Oerlikon Master Controller.

shall not trip out the high-tension oil-switch and so cut off the lighting and control circuits.

On motor-coaches, however, it is the general practice to supply the lighting and control circuits from an auxiliary transformer. In these cases it is the general practice to insert fuses in the secondary circuit of the main transformer and an automatic oil-switch in the primary circuit (see diagram of the wiring of the motor-coaches on the L.B. and S.C. Railway, p. 230).

The oil-switches may be closed manually, electrically, or pneumatically. When electric or pneumatic control is adopted and an auxiliary transformer is also installed, the main oil-switch is controlled from the reversing cylinder of the master controller.

It is not the practice to interrupt the primary circuit of the main transformer when power is cut off from the motors, since this procedure

* In some cases fuses are used as an additional protection.

is liable to set up surges which will produce breakdowns in the insulation of the transformer and high-tension wiring.*

In order to avoid the concentration of excessive voltage on the end turns of the primary winding of the transformer when this is switched into circuit, it is the practice of some continental firms to insert a resistance temporarily in this circuit during the switching operation. The oil-switch is provided with duplicate contacts (which are insulated from one another), and the auxiliary contacts are connected to the main contacts through a resistance. Thus, when the switch is operated, the circuit is first closed through the auxiliary contacts and the resistance.

FIG. 199.—Oerlikon Electrically-operated Oil-switch with Oil-immersed Switching Resistance.

Fig. 199 shows an electrically-operated switch of this type developed by the Oerlikon Co. for electric locomotives.

The oil-switches, current and potential transformers, and all high-tension protective devices must be located in a steel "high-tension" compartment. The doors of this compartment must be mechanically interlocked with the current collectors, so that the doors cannot be opened when the collectors are in contact with the overhead line. The opening of the doors usually earths the high-tension circuit, and in some cases the current collectors cannot be raised when the doors are open.

(See Chapters XVI and XVII for further details.)

EXAMPLES OF TYPICAL CONTROL SYSTEMS FOR SINGLE-PHASE MOTORS

All the control equipments in operation on the single-phase railways of this country are on the contactor system, and are arranged for multiple-

* In this connection see *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 179, p. 92, paper on "The Electrification of the Morecambe and Heysham branch lines of the Midland Railway," by Messrs. J. Dalziel and J. Sayers.

unit control. These equipments provide excellent examples of the application of the contactor system of control to motor-coach trains.

The equipments on the Midland Railway (Morecambe-Heysham branch lines) were supplied by the Westinghouse and the Siemens Companies for the control of series motors, while the equipments for the suburban lines of London, Brighton, and South Coast Railway were supplied by the Allgemeine Elektrizitäts Gesellschaft (A.E.G.) and control compensated repulsion motors. In each case the motors are about 150 H.P., and are controlled in pairs—i.e. two motors are supplied from one transformer and group of contactors. Moreover, a different method of transition is adopted for the respective equipments. Thus, in the A.E.G. equipments the motor circuit is opened (as in Fig. 174); in the Westinghouse equipment a preventive coil is used (as in Fig. 175); while in the Siemens equipments the transformer is provided with two secondary windings and two cross-connected preventive coils (as in Fig. 179).

A diagram showing the principal connections of the control and motor circuits for the **A.E.G. equipments** is given in Fig. 200.

In these equipments three sets of transformers are provided, viz. (a) the main transformers, of which there are two for each motor-coach, each transformer supplying two motors; (b) the exciter auto-transformers, one for each pair of motors; * (c) the auxiliary transformers, one for each motor-coach, which supply the control circuit, lighting, and compressors at 300 volts.

The secondary winding of each main transformer provides voltages of 450, 580, 640, and 750 volts, and the various tappings are connected to the motors by means of contactors with duplicate contacts.†

The contactors are electrically operated with single-phase current, and auxiliary contacts are provided for electrically interlocking the various contactors against incorrect operation. Thus the operating coil of contactor 4 is connected in series with the auxiliary contacts on contactors 5, 6, 7, so that contactor 4 cannot close unless these contactors are open. Similarly, contactor 5 cannot close unless contactors 4, 6, 7 are open.

Contactors 2 and 3 control the ratios of the exciter transformer, and therefore enable the excitation flux of the motor to be changed without changing the transformer (or cross-) flux. At starting (controller notch 1), the excitation flux is reduced below the normal value, in order to avoid excessive currents in the coils short-circuited by the brushes. Intermediate speeds (corresponding to controller notches 2, 3, 4) are obtained by voltage regulation with normal excitation flux in the motor. The highest speed (controller notch 5), however, is obtained by weakening the excitation flux; and in order to obtain satisfactory commutation under these conditions, the commutating-pole portion of the stator winding is excited from the exciter transformer in such a manner as to provide the requisite commutating flux.‡

* The auto-transformer for each pair of motors consists of two separate windings (one for each motor) and a common magnetic circuit.

† A reference to Fig. 200 will show that the two motors supplied from each main transformer are not permanently connected in parallel. Each contactor is, therefore, provided with duplicate contacts for effecting the parallel connection of the motors when the contactor closes.

‡ See Chapter V, p. 73, for a discussion of commutation phenomena at high speeds.

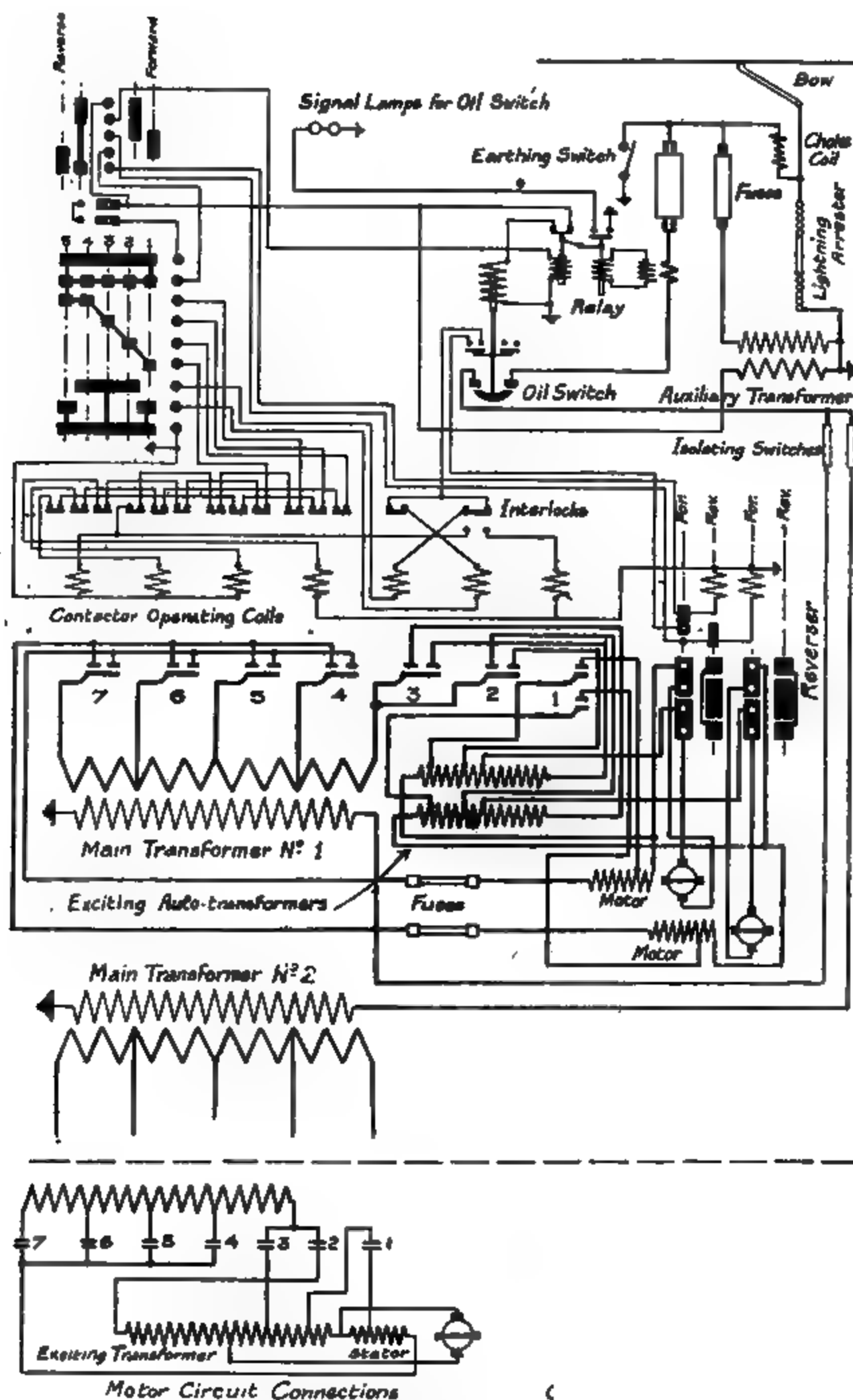


FIG. 200.—Connections of Motor and Control Circuits for A.E.G. Compensated-repulsion Motors (London, Brighton, and South Coast Railway).

The reverser is of the throw-over drum type, and is operated by two solenoids.

The master controller is provided with two cylinders, one for controlling the contactors, and the other for controlling the reverser. The main cylinder has five notches, and is fitted with a "dead-man's handle" of similar design to that illustrated in Fig. 146 (p. 173).

The main automatic oil-switch is electrically operated, and is controlled by low-voltage and overload relays. A reference to Fig. 200 will show that this switch is electrically interlocked with the control circuit, so that, when the oil-switch opens, the control circuit is automatically interrupted. Signal lamps are fixed in each driving compartment to indicate to the driver the opening of the oil-switch.

The **Westinghouse and Siemens equipments** installed on the motor-coaches operating on the Midland Railway (Morecambe-Heysham branch lines) possess the special feature that they can be operated from the same master controller, notwithstanding that, in one case, the control is on the electro-pneumatic system with electric interlocking; while, in the other case, the control is on the "all-electric" system with mechanical interlocking.

Diagrams showing the principal connections of the control and motor circuits of these equipments are given in Figs. 201, 202. The control circuit in each case is supplied at 150 volts from an auxiliary transformer.*

In the **Westinghouse equipment** the main transformer is of the oil-cooled "auto" type, and is provided with six tapings.

The "switch group" consists of six electro-pneumatically operated contactors, which are connected to the tapings of the main transformer and to a preventive coil in the manner shown in Fig. 175 (p. 209). The centre point of the preventive coil is connected to the motors through two contactors, *A*,† (called "line switches"), which are controlled from the reversing cylinder of the master controller. These contactors are electrically interlocked with those forming the "switch group," so that the latter cannot be operated until the line switches are closed. Auxiliary contacts are also provided on the "switch group" for interlocking these contactors against incorrect operation.

The reverser is of the throw-over drum type, and is electro-pneumatically operated.

The master controller is arranged on the "dead-man's handle" principle, and is provided with separate handles for reversing and speed control. When *either* the forward or the downward pressure on the main handle is released, the control circuit is interrupted at the bridging contacts *D* on the main cylinder.

The main automatic oil-switch *E* is electro-pneumatically operated. When the switch opens on overload, it can only be reset by returning the driving handle of the master controller to the "off" position.

In the **Siemens equipments** (Fig. 202) the main transformer *T* is

* Further details of these equipments will be found in *The Electrician*, vol. 61, pp. 324, 363, 371.

† These contactors were inserted to provide for a break between the motor circuits, and to prevent the motors from acting as generators if the coach were hauled by a locomotive, with the reverser in the incorrect position.

provided with two secondary windings, each giving the full voltage for one motor. Each secondary winding is provided with three tappings,

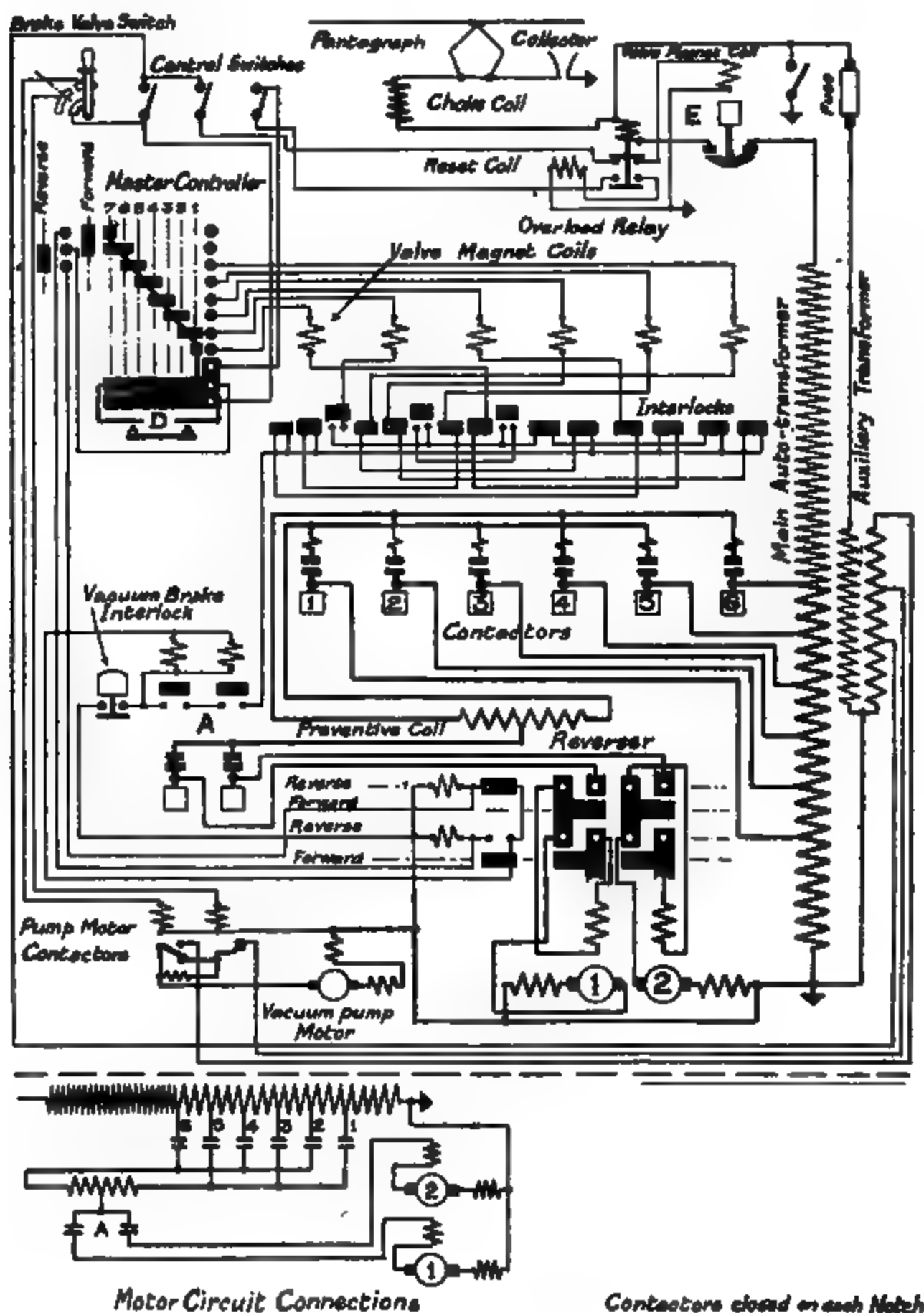


FIG. 201.—Connections of Motor and Control Circuits for Westinghouse Single-phase Series Motors (Midland Railway).

and the tappings are connected to the motors in the manner discussed above (see Fig. 179, p. 212).

The contactors for speed regulation are divided into two groups (corresponding to the two secondary windings), and each group consists of four electrically-operated contactors, which are mechanically

✱ *Holding-in' Coil*

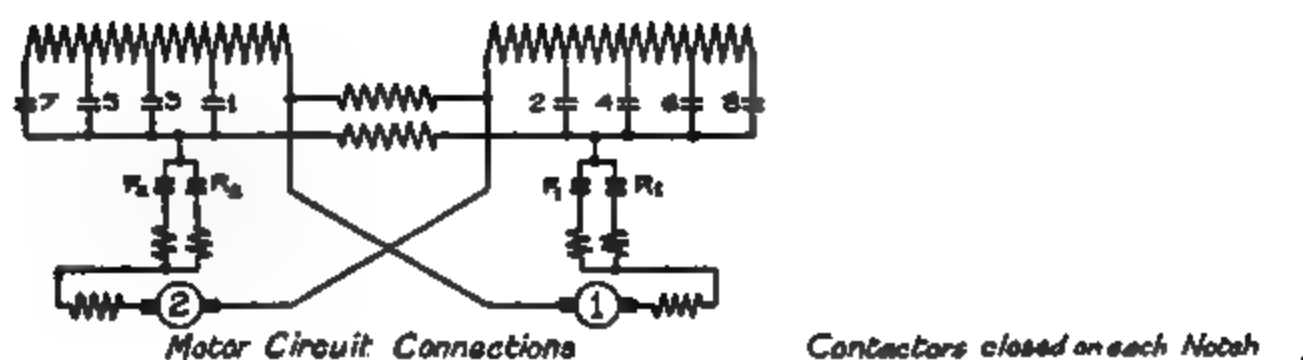


FIG. 202.—Connections of Motor and Control Circuits for Siemens Compensated-series Motors (Midland Railway).

interlocked to prevent more than one contactor being closed at the same time.

A separate reverser—in the form of two contactors—is provided for each motor. These contactors are represented in Fig. 202 at $F_1, F_2; R_1, R_2$.

The main automatic oil-switch *E* is of the electrically-operated type, and is provided with an overload relay, the latter being interlocked with the control circuit, so that the switch cannot be reset until the handle of the master controller has been returned to the "off" position.

An excellent example of the control of doubly-fed motors on the multiple-unit system is to be found on the motor-coach trains operating on the **Philadelphia-Paoli** section of the Pennsylvania Railroad.* The trains are made up entirely of motor-coaches, each of which is equipped with two 225-H.P., 6-pole, 25-cycle, doubly-fed Westinghouse motors and electro-pneumatic control. The motors are started as repulsion machines, and operate with repulsion connections up to a speed of about 15 m.p.h. Above this speed the connections are changed to series, with a double feed to the armature and excitation windings.

A simplified diagram of the connections of the control and motor circuits is given in Fig. 203. It will be observed that the two motors of each motor-coach are permanently connected in series, and that rheostats are inserted in the motor circuit on some of the notches. The various combinations for repulsion and series working are obtained by the use of a group of nine electro-pneumatic contactors, of the type illustrated in Fig. 185, which are interlocked electrically to provide against incorrect operation.

The control is arranged for automatic acceleration, and, to enable this to be carried out with the repulsion and series connections of the motors, special features have had to be introduced into the accelerating relay. For instance, the operating current of the relay, corresponding to a given tractive-effort of the motors, must be greater during repulsion working than during series working. In the equipments under consideration the two settings of the relay have been obtained by the use of a specially-weighted plunger and an additional winding, the latter being excited from the battery supplying the control circuit. The lower setting is obtained by energising this coil, which lifts the weight from the plunger of the relay, while the higher setting is obtained by opening the circuit of this coil, so that the weight is now added to the plunger. The coil is energised from the master controller at the same time as the motor connections are changed.

The control circuit is supplied from a single-phase (induction) motor-generator set operating in parallel with a battery. A low-voltage relay is connected to the motor for the purpose of disconnecting the generator from the battery in case of failure of the alternating-current supply. The control-circuit cable consists of ten wires.

The master controller is similar to that shown in Fig. 197: it is provided with a "dead-man's handle" and emergency contacts which energise an electro-pneumatic valve in the train-pipe of the air-brake. This device is operative when the handle is returned to the central or neutral position. In service the handle is returned to the first notch (see Fig. 203), which forms the "off" position for the motor and control circuits. Each master controller is provided with two plug switches which control the main oil-switch and the reset coil of the overload relay. The plug for operating these switches is chained to the handle of the controller, and, since this handle is removable, the circuit through the plug switches can only be established at the driving master controller.

* For details of the equipment see *Electric Journal*, vol. 12, p. 536.

As a further example of the control of doubly-fed motors, we may consider the control equipment on the locomotive supplied by the A.E.G. to the Rhaetian Railway (Engadine District, Switzerland).

The locomotive is equipped with two 350-H.P. doubly-fed motors and contactor control. The motors start with repulsion connections,

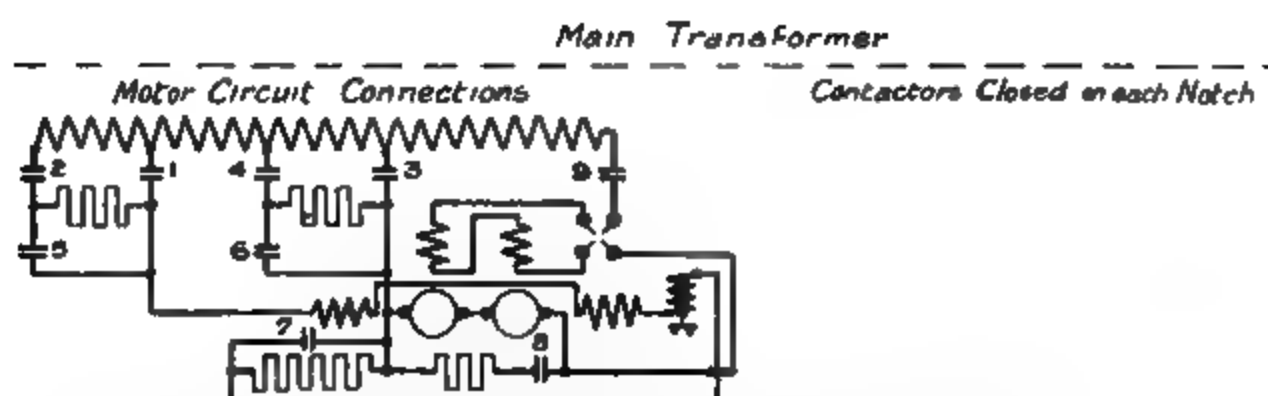


FIG. 203.—Connections of Westinghouse Electro-pneumatic System for Automatic Control of Doubly-fed Motors. NOTE.—The control-circuit couplers are not shown. The interlocks are shown in "open" position of contactors.

and operate with these connections up to a certain speed, when the connections are changed to series, with a double feed to the armature and excitation windings. The voltages applied to the various circuits of the motors are regulated from the master controller in accordance with the indications of a speed indicator at the driving platform.

The principal connections of the motor circuits are shown in Fig. 204.

The main transformer supplies both motors and all the auxiliary apparatus on the locomotive. For control purposes the secondary winding is provided with fourteen tapings, which are connected to a corresponding number of contactors *A*. The latter are arranged in two groups, with a preventive coil *B* connected between the groups in the usual manner. The motors are connected in parallel between the centre point of the preventive coil and the terminal *O* of the secondary winding.

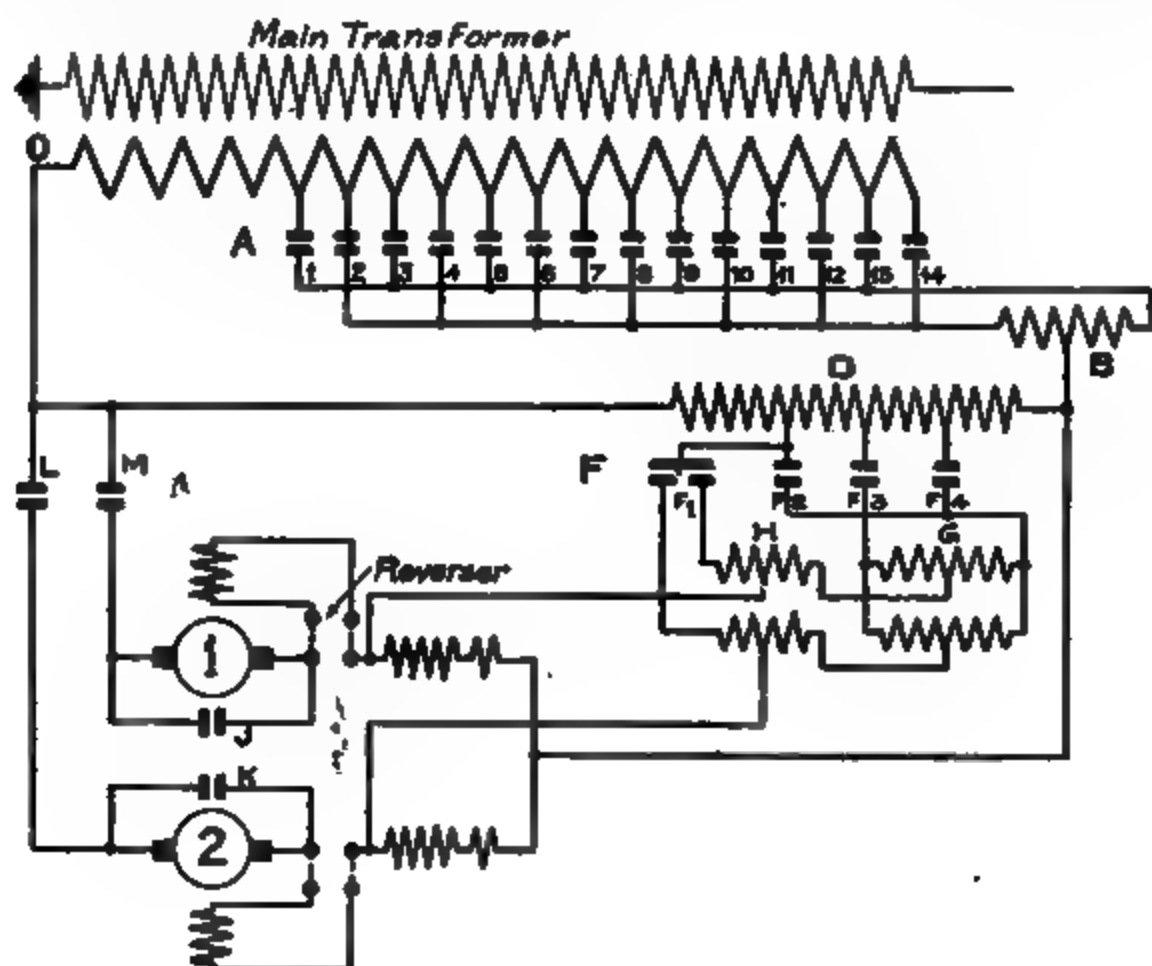


FIG. 204.—Motor Circuit Connections for A.E.G. Doubly-fed Motors.

An auto-transformer *D* is connected in parallel with the motors, and is provided with three tapings, which are connected to a group of contactors *F*. These contactors are connected to two groups, *G*, *H*, of preventive coils—one group for each motor—from which connections are taken to the motors, as shown in the diagram.

Two other contactors, *J*, *K*, are connected respectively across the armature of each motor. When these contactors are closed the motors

operate as repulsion machines, and are supplied at a suitable voltage from the theappings on the main transformer. Above a certain speed the motors are converted into doubly-fed machines by opening contactors *J*, *K* and closing contactors in the group *F*.

The reverser is of the throw-over drum type, and is interlocked electrically with the contactors *L*, *M*, forming the "line switches," so that the latter cannot close until the former is set for the required direction of running.

The master controller is provided with two handles, one for regulating the terminal voltage of the motors, and the other for controlling the reverser, the contactors for repulsion working, and the contactors

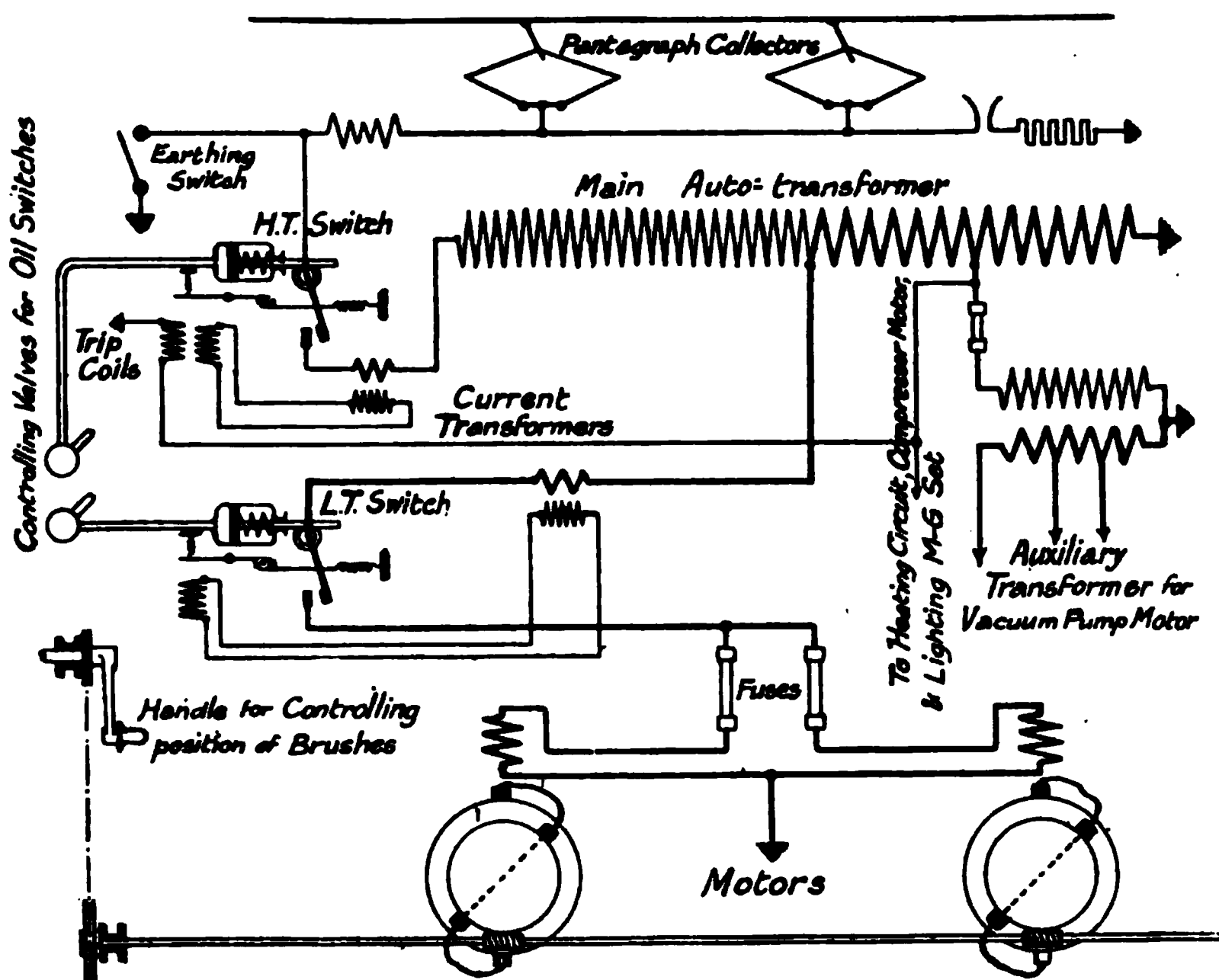


FIG. 205.—Connections for Control of Brown-Boveri-Déri Motors.

for regulating the voltage applied to the armature and excitation windings for doubly-fed working.

The control equipment for Déri brush-shifting repulsion motors is characterised by its extreme simplicity and the absence of contactors and auxiliary apparatus. This will be apparent from an inspection of Fig. 205, which shows the principal connections* adopted by Brown, Boveri & Co. in locomotives equipped with Déri motors. The oil-switches in the high-tension and low-tension circuits are operated pneumatically, and the position of the movable brushes is controlled by a handwheel. The low-tension oil-switch is provided with an overload trip-coil, while the high-tension oil-switch is provided with overload and low-voltage trip coils.

* The lighting and instrument circuits are not shown in Fig. 205, in order that this diagram may be strictly comparable with Figs. 200, 201, 202, 203, 206.

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FIG. 208.—Motor and Control Circuit Connections for Combined Alternating-current and Continuous-current Operation (Westinghouse Co.). NOTE.—Interlocks are shown in "open" position of contactors. Numbers adjacent to interlocks refer to contactors to which the interlocks belong

The heating circuit, compressor motor, and motor-generator set (for supplying the lighting circuits) are supplied from a tapping on the main auto-transformer, while an auxiliary transformer is provided for supplying the vacuum pump motor (operating the brakes) at variable voltage.

An interesting control system for the dual operation of series motors on alternating-current and continuous-current circuits has been developed by the Westinghouse Co. for certain passenger and freight locomotives on the New York, New Haven, and Hartford Railroad. These locomotives have to be capable of running over the tracks of the New York Central Railroad—which are supplied with continuous current at 650 volts—in addition to operating on the single-phase 11,000-volt system of the New Haven and Hartford Railroad.

The locomotive motors are of the Westinghouse neutralised-series type with forced neutralising winding, and are capable, therefore, of operating with either continuous current or alternating current. The freight locomotives are each equipped with eight motors, rated at 170 H.P. 275 volts (alternating current) and 200 H.P. 325 volts (continuous current). The motors are arranged in pairs, and the motors of each pair are permanently connected in series. For alternating-current operation the four pairs are connected in parallel, while for continuous-current operation the four pairs are arranged in two groups—the two pairs of each group being connected in parallel—and controlled on the series-parallel system with “bridge” transition.

The various combinations between the motors, rheostats, and transformer tapplings are effected by electro-pneumatic contactors (or unit switches) of the standard Westinghouse type. There are in all thirty-two contactors, of which seventeen are used for alternating-current control and nineteen for continuous-current control, four contactors being common to both control systems.

The control circuit is supplied from a 32-volt battery, and the whole of the control operations are effected by a single master controller (of the type illustrated in Fig. 196) in conjunction with a change-over switch.

The principal connections of the motor circuits and the control circuits are shown in Fig. 206, which, with the chart of switch operations, is self-explanatory. It should be observed that, in alternating-current operation, the transition is by the method shown in Fig. 178 (p. 211), four of the contactors, connected to the tapplings of the transformer, being closed on each of the nine “running” notches of the controller.

The dual operation considerably complicates the wiring for the control and motor circuits. However, the use of a common master controller and a change-over switch possesses advantages over the use of separate master controllers for alternating-current and continuous-current operation, since not only is a reduction in the total weight of the control equipment effected, but increased safety is obtained.

With similar locomotives, equipped for alternating-current operation only, nine running points are obtained with the use of sixteen contactors, the number of tapplings and the method of transition being the same as above. The control equipment of these locomotives, however, is 3.65 tons lighter than that for the above locomotives.*

* For detailed weights of the control equipments in the two locomotives, see a paper on “Trunk Line Electrification” by Mr. W. S. Murray (*Transactions of the American Institute of Electrical Engineers*, vol. 30, p. 1431).

CHAPTER XI

THE CONTROL OF THREE-PHASE RAILWAY MOTORS

General.—The methods of obtaining a range of speeds from polyphase railway motors have been considered in Chapter VI. These methods may be summarised as follows: (1) rheostatic control, (2) control by changing the number of poles, (3) cascade control, (4) combined cascade and pole-changing control. Generally, rheostatic control is required with the cascade and pole-changing systems for the purpose of regulating the starting torque and acceleration. Hence, in the majority of cases, a rheostat forms part of the control equipment, and apparatus will therefore be required for cutting in and out the resistance as occasion demands. The class of apparatus suitable for performing the latter function will depend on whether or not the locomotives or motor-coaches are to be operated on the multiple-unit system.

In the selection of a rheostat for a polyphase motor, it is important to keep in view the effects of inductance in the rotor circuit on the performance of the motor. This is particularly important when cascade control is to be adopted, as any additional inductance in the secondary motor will adversely affect the power-factor and overload capacity of the combination.

Grid rheostats, of the type used in electric railway work, are not devoid of self-induction. Tests on rheostats of this type have shown that, on alternating-current circuits of 25 frequency, there is a phase-displacement of about 5 degrees between the current in the rheostat and the voltage across its terminals.

On the other hand, a liquid rheostat may possess a slight capacity, which will tend to improve the power-factor of the motor with which it is used. Liquid rheostats are, therefore, preferable to grid rheostats when cascade control is to be adopted.

In addition to the non-inductive property of a liquid rheostat, this apparatus has the advantage that the resistance can be cut out in such a manner that a perfectly uniform torque can be obtained throughout the period of rheostatic acceleration.

As developed at the present time for locomotive service, the liquid rheostat is automatic in its action, and is capable of dissipating a considerable amount of power without overheating, while the controlling and regulating apparatus can readily be adapted for multiple unit operation. The further consideration of these features, however, must be deferred until the general methods of control have been discussed.

Rheostatic Control.—The rheostatic method of control is the simplest but least efficient of the above methods for regulating the speed of polyphase motors. Only one economical running speed can be obtained, and approximately one-half of the energy supplied to the motors during the accelerating period is wasted in the rheostats. This method of control is used for the light locomotives and motor-cars operating on the Swiss mountain railways, and it is also used for the 100-ton locomotives operating on the Cascade Tunnel system of the Great Northern Railway, U.S.A.

The control equipments on the Cascade Tunnel locomotives are arranged for multiple-unit operation, while those on the locomotives and motor-cars operating on the Swiss mountain railways are arranged for direct control (*i.e.* single operation). In these (latter) equipments the controllers do not present any special features, since they are an adaptation of industrial controllers for polyphase motors.

For the purpose of comparison with the multiple-unit system, described below, we give in Figs. 207, 208 diagrams of the **connections and development of three-phase rheostatic controllers** for industrial service. Fig. 207 refers to a controller suitable for a reversible motor of moderate size and voltage (*e.g.* 200 H.P. 440 volts), while Fig. 208 refers to a controller suitable for a reversible motor of high voltage. The controllers differ only in the method of controlling the stator circuits. Thus in Fig. 207 the stator circuits are controlled by segments on the main cylinder, while in Fig. 208 the stator circuits are separate from the main cylinder, and are connected to a mechanically operated double-throw triple-pole oil-switch, which is fixed to the back of the controller and is operated by a cam device on the controller shaft.

Each phase of the rotor rheostat is divided into four sections, and the fourteen controller points are obtained by arranging that the sections of the rheostat are cut out *successively* from each phase. An unbalancing of the phases will therefore occur on some of the notches, but this is not objectionable if the rheostat is graded so that a minimum of unbalancing is obtained throughout.* This method of control considerably simplifies the controller, and has obvious advantages over the symmetrical, or balanced, method of control (in which the resistance is cut out simultaneously from each phase). For controllers of the “face-plate” type, however, the latter method is more convenient.

It is apparent that for multiple-unit operation the rotor portion of the cylinder of the above controllers must be replaced by an equivalent group of contactors.

The reversing, in the case of low-voltage motors, must be performed by means of either a group of contactors or an electrically-operated reverser; but with high-voltage motors the reverser must take the form of a self-contained enclosed switch of either the oil-break type or the enclosed air-break type as described below (see Fig. 219).

The operating coils of the contactors may be supplied with single-phase current †—obtained from an auxiliary transformer, which also

* An unbalancing up to 40 per cent. in the relative values of the currents in the phases of a three-phase rotor does not seriously affect the operation of the motor for industrial purposes. In control equipments for electric locomotives, the maximum permissible unbalancing is governed by the maximum permissible variations in the tractive-effort when the locomotive is accelerating its maximum load.

† Single-phase contactors are described in Chapter X.



FIG. 207.—Connections and Development of Three-phase Rheostatic Controller for Reversible Motor of Moderate Output and Low Voltage.

FIG. 208.—Connections and Development of Three-phase Rheostatic Controller for Reversible Motor of Moderate Output and High Voltage.

supplies current for lighting—or the control circuit may be operated with continuous current, which may be obtained from accumulators or a motor-generator set.

With the rotor circuit connections arranged as in Fig. 208, it is apparent that fourteen contactors will be required to obtain fourteen notches. In the equipments for the Cascade Tunnel locomotives, however, thirteen notches have been obtained with the use of only nine contactors in the rotor circuit, the sections of the rheostats being arranged for series and parallel groupings. The **rotor-circuit connections** are shown in Fig. 209, which, with the chart of switch operations, is self-explanatory.

The **connections and development** of a suitable **master controller** to perform these operations are shown in Fig. 210. This figure also shows the connections of the reverser (which, for the low-voltage motors on these locomotives, consists of five contactors), and the method of interlocking the contactors and reverser.

Control by changing the number of poles.—This method of control is the simplest of the multi-speed methods, and enables two, three, or four running speeds to be obtained from a single motor, or a group of motors connected in parallel.

The **multi-speed methods of control** (viz. the pole-changing and cascade combinations) can be considered as the adaptation (and extension) of the series-parallel system of continuous-current control to polyphase alternating-current motors. Thus the simple rheostatic and the two-speed changeable-pole, or cascade, control of three-phase motors correspond respectively to the rheostatic and series-parallel control of two continuous-current motors. The diagrams given in Fig. 111 (p. 143), showing the losses in the starting rheostats for rheostatic and series-parallel control, will also represent approximately the relative losses in the rheostats for the rheostatic and two-speed control of alternating current motors, since, in changeable-pole motors, the losses in the rotor circuit, corresponding to a given starting torque, are inversely proportional to the number of poles (see p. 110). The four-speed changeable-pole control, however, will show greater economy in starting than the double series-parallel system in continuous-current equipments, as in the former case four speeds are possible (which are usually in the ratio of either $1 : 1.5 : 2 : 3$, or $1 : 1.33 : 2 : 2.66$), while in the latter case only three speeds (in the ratio of $1 : 2 : 4$) can be obtained.

The methods of obtaining a number of speeds by pole-changing windings have been considered in Chapter VI, and are summarised here for convenience. Thus two speeds can be obtained by providing each motor with either two separate stator windings (each wound for the required number of poles) or a single pole-changing winding of the type shown in Fig. 81 (p. 106). Three speeds can be obtained by providing two stator windings, of which one is a pole-changing winding; while four speeds are possible by the provision of two pole-changing windings on the stator of each motor.

The three- and four-speed combinations, however, are only practicable if each motor has a squirrel-cage rotor, as, with the standard method of connecting the stator windings of changeable-pole railway motors

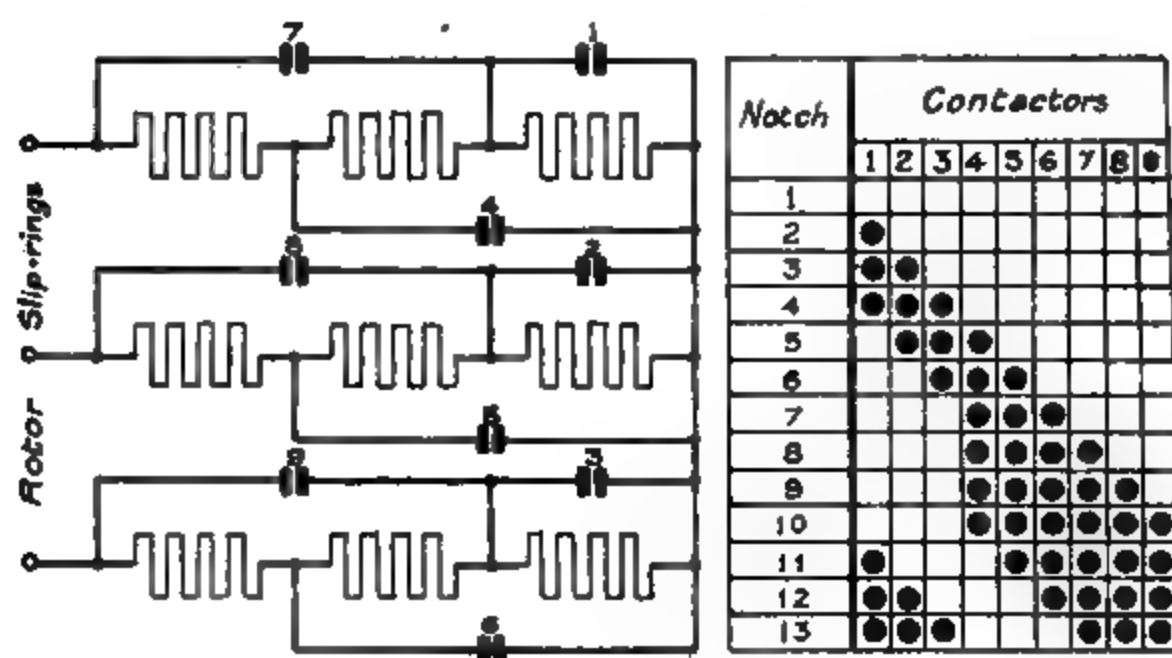


FIG. 209.—Rotor-circuit Connections for Rheostatic Control of Three-phase Railway Motors.

Fig. 210

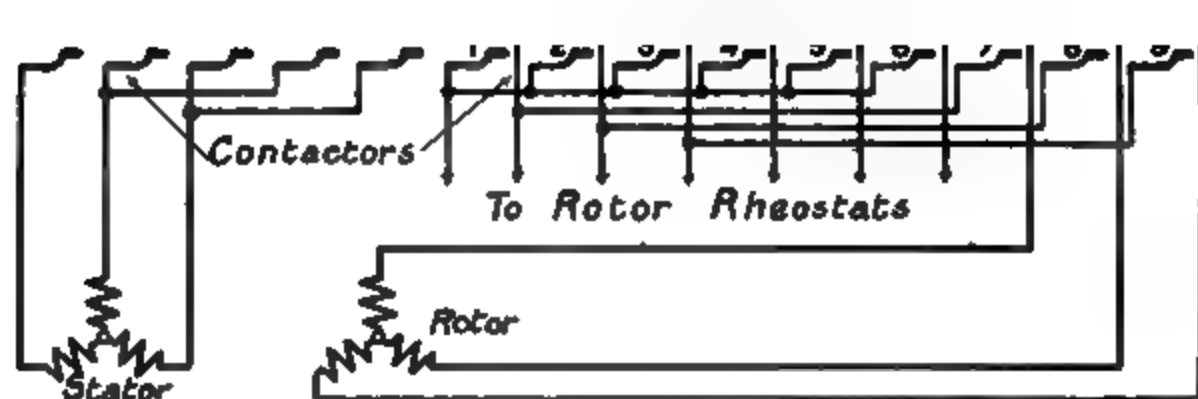


FIG. 210.—Connections and Development of Master Controller for Rheostatic Control of Three-phase Railway Motors according to method of Fig. 209.

(see Fig. 81, p. 106), two rotor windings with the necessary slip-rings are required for each pole-changing winding on the stator.

In each case the regulation of the torque and speed during starting and acceleration must be performed by rheostatic control, or, in the case of machines with squirrel-cage rotors, by the variation of the voltage applied to the stator.

The **type of rheostat for locomotives** requires careful consideration, as the maximum variation of the tractive-effort during the accelerating period must be limited to such values that slipping of the driving wheels cannot occur when the locomotive is accelerating its maximum load. If grid rheostats are adopted, it is apparent that the grading of the resistance will be different for each rotor winding. Hence either duplicate rheostats, suitably graded for each rotor winding, or a single rheostat, with two groups of contactors, will be required.

When multiple-unit operation of the locomotives is not required, the provision of duplicate rheostats of the face-plate type forms the simplest solution; but for multiple-unit operation it will be necessary to provide contactors, and under these conditions the adoption of grid rheostats involves considerable complication of the control circuit. An automatic liquid rheostat, however, will provide the correct grading for both of the rotor windings. This type of rheostat, therefore, possesses considerable advantages over grid rheostats for multiple-unit operation with changeable-pole motors.

With motors having squirrel-cage rotors the **control of the torque during starting** must be accomplished by the variation of the voltage applied to the motor, for which purpose auto-transformers with multiple tapplings are suitable. The tapplings may be successively connected to the stator winding by means of either a drum type controller or a group of contactors, the latter method being suitable when multiple-unit operation is required. In order to avoid short-circuiting the sections of the transformer winding, the transition from one tapping to the next may be made through either a preventive coil or a preventive resistance. The principles of this method of voltage control have been discussed in detail in Chapter X, in connection with the control of single-phase motors, and the only differences between the present case and that discussed in Chapter X are: (1) The supply is polyphase instead of single-phase; (2) the motors are wound for the line voltage; (3) the transformers are only used for starting purposes.

Since the lowest voltage required from the transformers is of the order of one-third the line voltage, an auto-transformer will offer several advantages over a transformer with separate windings. On three-phase circuits, two auto-transformers, connected in "V" (open-delta), can be used—instead of three transformers connected in star or delta—without unbalancing the system. Moreover, the V-connected auto-transformers only require two controllers (or groups of contactors) for each motor (or group of motors) supplied from the transformer.

As an **example of the method of operation of the control apparatus for changeable-pole motors**, we will consider a four-speed equipment in which the motors have two stator windings (to give 16/8 and 12/6 poles) and squirrel-cage rotors. The control of the torque during start-

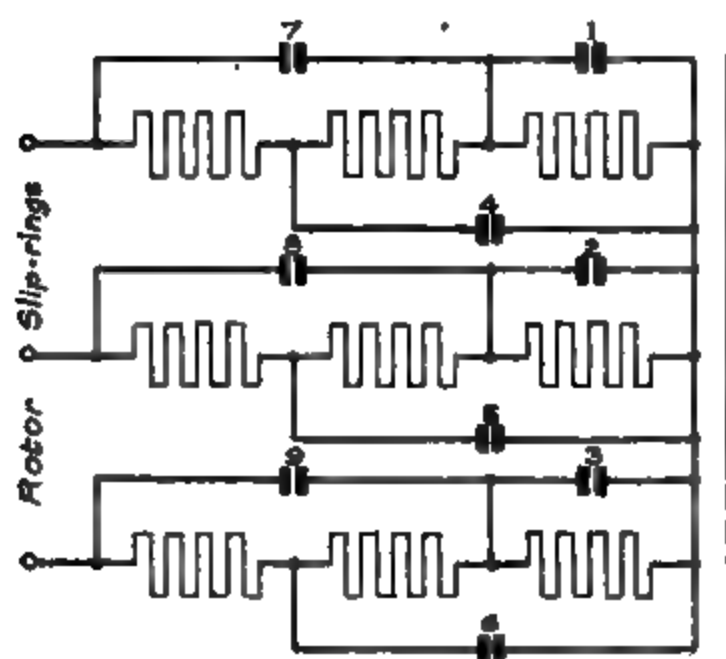


FIG. 209.—Rotor-circuit Connections for Rheostatic Control of Three-phase Railway Motors.

FIG. 210.—Connections and Development of Master Controller for Rheostatic Control of Three-phase Railway Motors according to method of Fig. 209.

(see Fig. 81, p. 106), two rotor windings with the necessary slip-rings are required for each pole-changing winding on the stator.

In each case the regulation of the torque and speed during starting and acceleration must be performed by rheostatic control, or, in the case of machines with squirrel-cage rotors, by the variation of the voltage applied to the stator.

The **type of rheostat for locomotives** requires careful consideration, as the maximum variation of the tractive-effort during the accelerating period must be limited to such values that slipping of the driving wheels cannot occur when the locomotive is accelerating its maximum load. If grid rheostats are adopted, it is apparent that the grading of the resistance will be different for each rotor winding. Hence either duplicate rheostats, suitably graded for each rotor winding, or a single rheostat, with two groups of contactors, will be required.

When multiple-unit operation of the locomotives is not required, the provision of duplicate rheostats of the face-plate type forms the simplest solution; but for multiple-unit operation it will be necessary to provide contactors, and under these conditions the adoption of grid rheostats involves considerable complication of the control circuit. An automatic liquid rheostat, however, will provide the correct grading for both of the rotor windings. This type of rheostat, therefore, possesses considerable advantages over grid rheostats for multiple-unit operation with changeable-pole motors.

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As an **example of the method of operation of the control apparatus for changeable-pole motors**, we will consider a four-speed equipment in which the motors have two stator windings (to give 16/8 and 12/6 poles) and squirrel-cage rotors. The control of the torque during start-

ing is effected by variation of the voltage applied to the motors, for which purpose auto-transformers with controllers are used.

The sequence of the control operations, in accelerating from stand-still to full speed, is as follows :—

(1) The reverser is set for the required direction of motion, and both pole-changing switches are closed to give the full number of poles for each winding.

(2) The motors are started on the lowest voltage of the auto-transformers, and the voltage is raised until the motors are operating with full voltage; the pole-changing switch for the 16-pole winding is then

opened, thereby allowing the speed to rise to approximately the synchronous speed corresponding to 12 poles.

(3) Next, the voltage is reduced, the 8-pole winding is connected in parallel with the 12-pole winding, and the voltage increased again, when the 12-pole winding is opened.

(4) The voltage is again reduced, the 6-pole winding is connected in parallel with the 8-pole winding, the voltage is raised to normal and the 8-pole winding is opened, thereby allowing full speed to be reached.

Cascade Control.—The cascade system of control requires two motors, of which at least one must be provided with a wound rotor and slip-rings; but for railway purposes it is the practice to provide both motors with slip-rings.

At starting, and for low speeds, the motors are connected in cascade—i.e. the secondary motor is supplied from the rotor

of the primary motor (see Fig. 78, p. 103)—while, for higher speeds, the secondary motor is either disconnected, and the primary motor operated alone, or both motors are operated in parallel.

The cascade system, as at present developed, is capable of several variations. Thus :—

(1) **For two speeds**, the primary and secondary motors are usually wound for the same number of poles, and the secondary motor may, or may not, be arranged for operating in parallel with the primary motor.

(2) **For three speeds**, the primary and secondary motors must be wound for unlike numbers of poles, and each motor must be capable of operating at the full line voltage.

(3) **For four speeds**, two alternative schemes are available, viz.

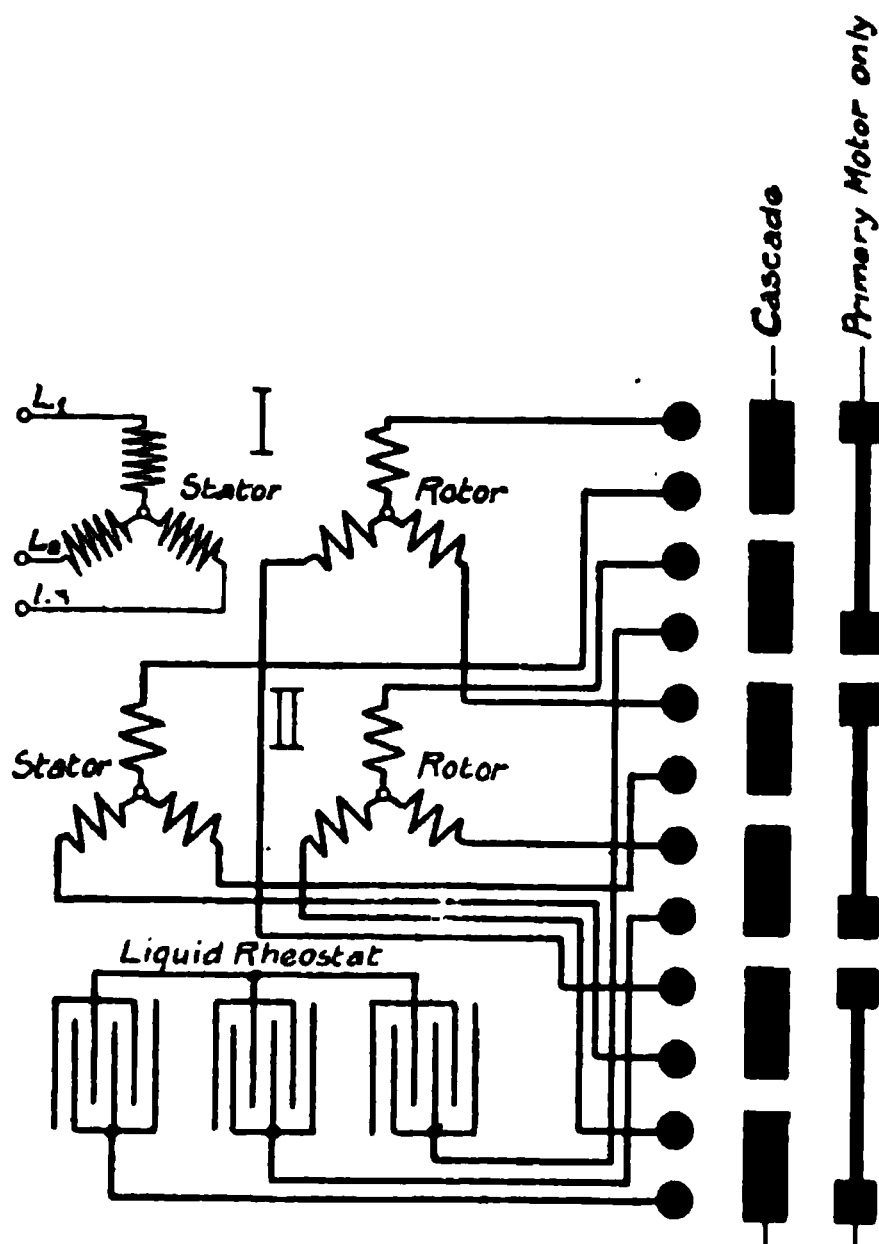


FIG. 211.—Connections and Development of Charge-over Switch for Cascade-single Control.

(a) the addition of a pole-changing winding to one of the motors of the three-speed combination; (b) the addition of pole-changing windings to both motors of the two-speed combination.

These variations of the cascade system may be designated respectively as (1) two-speed cascade-single control, (1a) two-speed cascade-parallel control, (2) three-speed cascade-single control, (3a) four-speed cascade-single pole-changing control, (3b) four-speed cascade-parallel pole-changing control.

Two-speed Cascade-single Control.—A diagram showing the combinations of the motors and rheostat for this method of control is given in Fig. 78 (Chapter VI, p. 103). These combinations may be conveniently made by means of a change-over switch, which is operated, electrically or pneumatically, from the master controller. The connections and development of a suitable drum-type change-over switch are given in Fig. 211.

When double motors are adopted, the rotor windings of the primary and secondary motors are usually connected together, and the stator winding of the secondary motor is connected to the rheostat during cascade working; this arrangement requiring only one set of slip-rings for each double motor.

In accelerating from stand-still to full speed the master controller must perform the following functions:—

- (1) Set reverser for the desired direction of motion.
- (2) Set change-over switch for cascade operation; connect stator winding of primary motor to supply.
- (3) Cut out resistance until the rheostat is short-circuited. (The speed will then be approximately equal to the cascade-synchronous speed of the motors.)
- (4) Interrupt the stator circuit of the primary motor; set change-over switch for single operation; insert full resistance in the rheostat; reconnect stator winding of primary motor to supply.
- (5) Cut out resistance until the rheostat is short-circuited.

Two-speed Cascade-parallel Control.—In this case the secondary motor must be capable of operating in parallel with the primary motor.

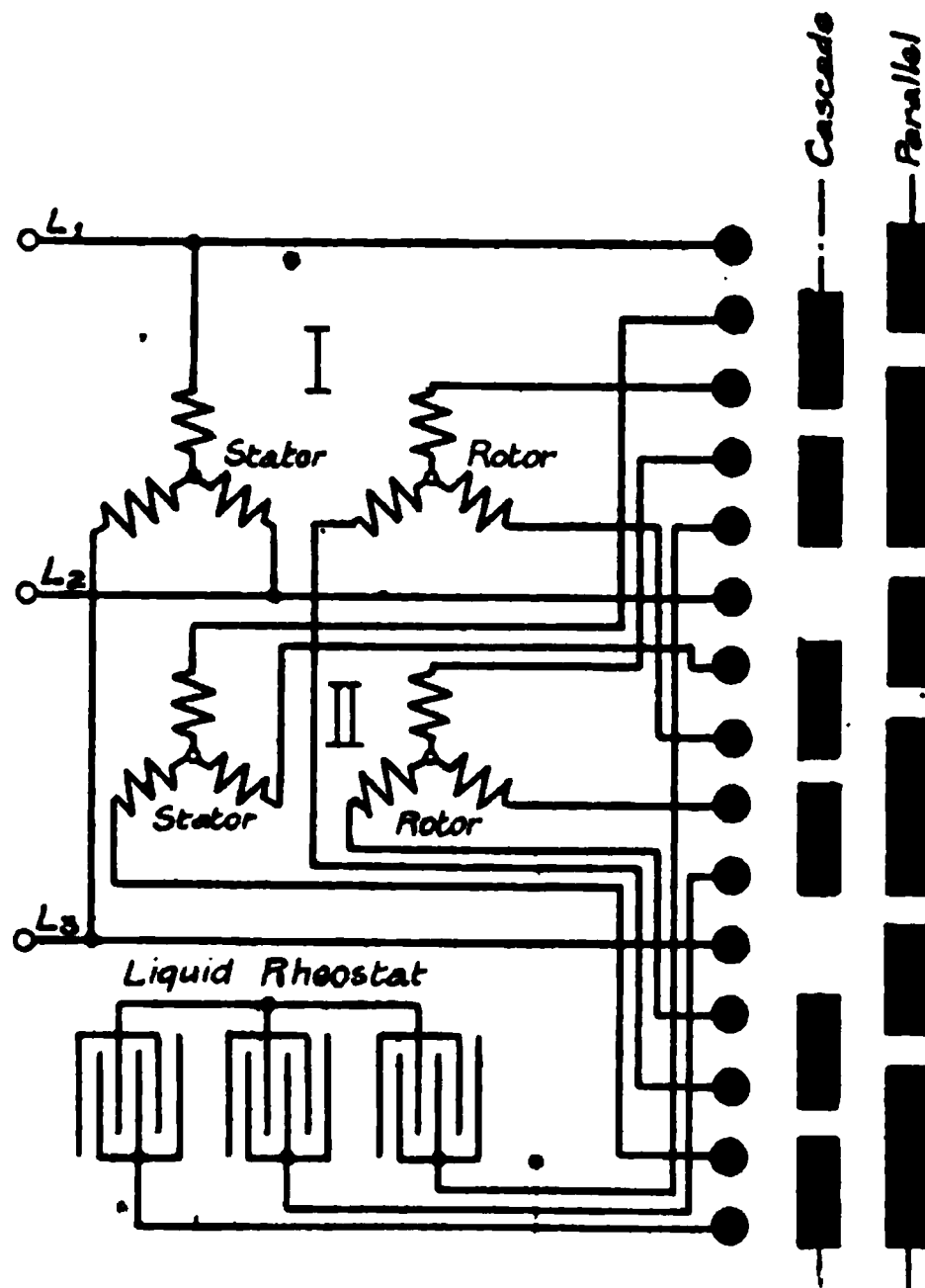


FIG. 212.—Connections and Development of Change-over Switch for Cascade-parallel Control. NOTE.—The primary and secondary motors are considered to be wound for a 1:1 ratio of transformation. If ratio of transformation is greater than unity, a regrouping switch (Fig. 213) is required for the secondary motor.

Obviously, this will be possible if both motors are designed for a 1 : 1 ratio of transformation. With high voltage motors, however, the ratio of transformation must be greater than unity. Hence, if the secondary motor is designed for a 1 : 1 ratio of transformation, it will have to be supplied from a transformer when operating in parallel with the primary motor. But if the secondary motor is designed for the same ratio of transformation as the primary motor, then, by suitably selecting the ratio of transformation in relation to the number of poles, it is possible to *regroup the stator winding of the secondary motor* for a 1 : 1 ratio of transformation. Under these circumstances cascade-parallel control can be adopted without the use of an auxiliary transformer.

The switch for regrouping the stator winding is usually of the drum



FIG. 213.—Connections and Development of Regrouping Switch for 12-pole Motor.

type and is mounted on the frame of the motor. With the exception of this regrouping switch and the means for energising it from the master controller, the control apparatus is practically identical with that for cascade-single control. The change-over switch, however, is not of identical construction in the two cases. A diagram of the connections and development of a suitable drum-type change-over switch is given in Fig. 212, which should be compared with Fig. 211.

The functions to be performed by the master controller in accelerating from standstill to full speed are as follows :—

- (1) Set reverser for the desired direction of motion.
- (2) Set change-over and regrouping switches on secondary motor for cascade operation ; connect stator winding of primary motor to supply.
- (3) Cut out resistance until the rheostat is short-circuited.

- (4) Interrupt the stator circuit of primary motor; set change-over and regrouping switches for parallel operation; insert full resistance in the rheostat; reconnect stator winding of primary motor (together with that of secondary motor) to the supply.
- (5) Cut out resistance until the rheostat is short-circuited.

Three-speed Cascade-single Control.—In this method the primary and secondary motors are wound for unequal numbers of poles, and are operated singly and in cascade.



FIG. 214.—Connections and Development of Change-over Switch for 3-speed Cascade Control.

The stator winding of the secondary motor will generally require to be subdivided and connected to a regrouping switch in order to obtain the correct ratio of transformation for cascade operation.

In Fig. 213 are given the connections and development of a suitable switch, of the drum type, for regrouping the windings of a 12-pole motor. Each phase of the stator winding consists of six groups of coils—one group per pair of poles. For cascade working these coils are connected in three parallel sets (each set comprising two groups of coils in series) and the phases connected in Δ ; while for parallel operation the coils are connected in series and the phases connected in star.

The change-over switch must have three positions, viz. :—

- (1) *Lowest speed (cascade)*, in which the rotor of the primary motor

is connected to the regrouped stator winding of the secondary motor, and the rotor winding of this motor is connected to the rheostat.

(2) *Intermediate speed*, in which the rotor of the primary motor is disconnected from the secondary motor and the latter arranged for connecting to the supply.

(3) *Full speed*, in which the rheostat is connected to the rotor winding of the primary motor and the secondary motor is disconnected from the supply and the rheostat.

The connections and development of a suitable drum-type change-over switch are indicated in Fig. 214.

Assuming, as above, the secondary motor to have a larger number of poles than the primary motor, the following functions must be performed by the master controller in accelerating from standstill to full speed :—

(1) Set reverser for the desired direction of motion.

(2) Set regrouping switch on secondary motor for cascade working and change-over switch to cascade position; connect stator winding of primary motor to supply.

(3) Cut out resistance until the rheostat is short-circuited.

[This will give the lowest economical running speed, which in this case corresponds approximately to the cascade-synchronous speed of the combination.]

(4) Interrupt stator circuit of primary motor; set change-over switch to intermediate position and regrouping switch for full voltage; insert full resistance in rheostat; connect stator winding of secondary motor to supply.

(5) Cut out resistance until the rheostat is short-circuited.

[This will give the intermediate running speed, which corresponds approximately to the synchronous speed of the secondary motor.]

(6) Interrupt stator circuit of secondary motor; set change-over switch to position for full speed; reconnect stator winding of primary motor to supply.

(7) Cut out resistance until the rheostat is short-circuited. [This will give the highest running speed.]

Combined cascade and pole-changing control (four-speed cascade-parallel control). In this method of control the primary and secondary motors are each wound for the same number of poles, but the windings are arranged so that the number of poles can be changed. If the poles are changed in the ratio of 2 : 1, the speeds obtainable will be in the ratio of 1 : 2 : 3 : 4. This variation of speed is too great for general railway service, and a maximum variation of 1 : 3 is generally sufficient for all conditions of passenger service.

Hence it will be necessary to change the poles in the ratio of either 1.33 : 1 (i.e. 8 : 6) or 1.5 : 1, so that the four speeds obtainable are in the ratio of 1 : 1.33 : 2 : 2.66, or 1 : 1.5 : 2 : 3 respectively. To meet these conditions it will be necessary to provide either—

(a) Two complete windings (each wound for the required number of poles) on the stator and rotor, or

(b) A single pole-changing winding on the stator in conjunction with either two rotor windings (designed for the required number of poles and phases), or a specially connected single rotor winding with a double set of slip-rings.

In the first case (a) both of the stator windings on the secondary

motor will require regrouping switches for cascade operation, while, in the second case (*b*), a regrouping switch, in addition to a pole-changing switch, will be required for the secondary motor.

In connection with the second case (*b*), the simplest pole-changing winding available for the above conditions is one in which the poles are changed in the ratio of 8 : 6 (*i.e.* 1.33 : 1), but when the winding is re-connected for the smaller number of poles it becomes a two-phase winding (see Fig. 83, p. 108). Hence, in order to render cascade control possible, the corresponding rotor winding must be of the two-phase variety. It is shown in Chapter VI (p. 112) that a single rotor winding can be arranged to form either an 8-pole three-phase winding or a 6-pole two-phase winding, without the change of any connections. Separate slip-rings, of course, are required for the three-phase and two-phase circuits.

The rheostat must be suitable for either the three-phase or the two-

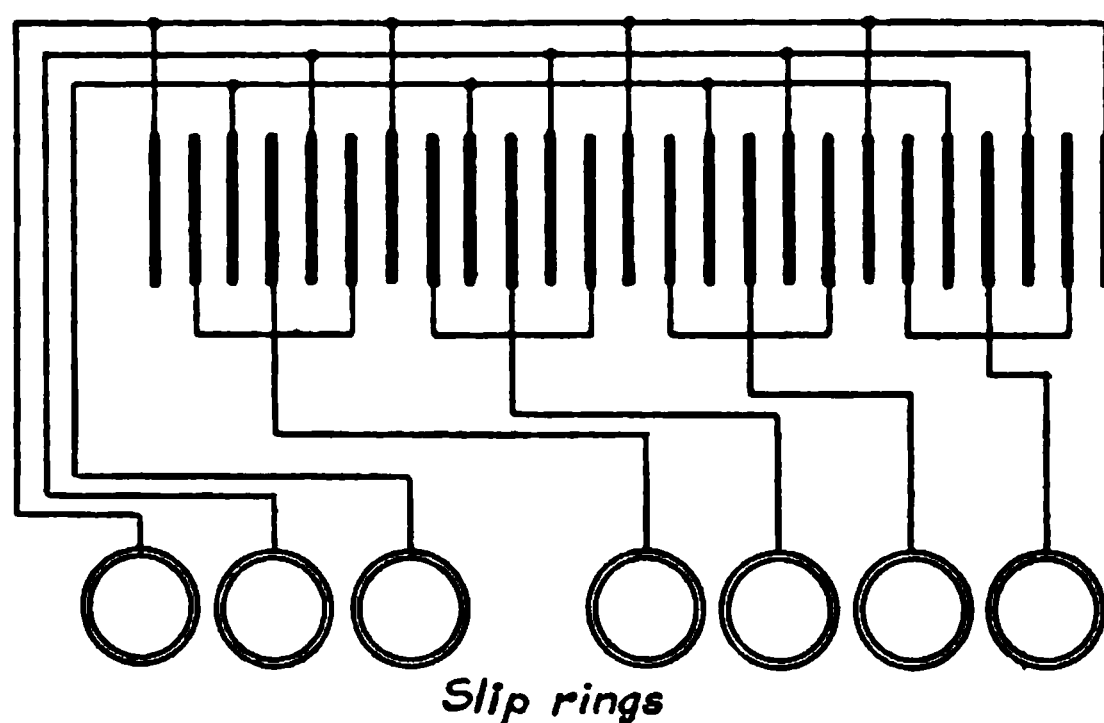


FIG. 215.—Connections of Rheostat Electrodes to Slip-rings for Three-phase and Two-phase Operation with Rotor Winding of Fig. 84.

phase rotor circuits. A single liquid rheostat with seven main electrodes connected to the slip-rings, as in Fig. 215, will satisfy this condition, provided that the rotor winding is connected in accordance with the scheme of Fig. 84 (p. 111). A reference to this diagram will show that when the motor is operating with three-phase current (*i.e.* 8 poles), there will be no potential difference between the two-phase slip-rings—since these are connected to the four neutral points of the winding—while, with two-phase operation (*i.e.* 6 poles), all the three-phase slip-rings will be at the same potential.

The two-phase current for supplying the stators of the motors can be obtained from the three-phase supply by means of two auto-transformers, connected according to the Scott (or “T”) system, as indicated in Fig. 216. With this method of connection the transformers need only be of relatively small capacity, since the largest portion of the input to the motor is supplied directly from the supply lines. A reference to Chapter VI (p. 113) will show that, if the stator winding is star-connected for three-phase working, and the full line voltage is used for two-phase operation, the flux in the latter case will be about 34 per cent. greater

than that in the former case. The normal flux, however, can readily be obtained by means of tapplings on the auto-transformers.

Reverting to the circuit diagram of Fig. 216, phase I of the motor is connected across the lines *B*, *C*, or, if normal flux is required in the motor, to tapplings *E*, *F* (giving 75 per cent. of the line voltage) on the auto-transformer T_1 ; while phase II is supplied through auto-transformer T_2 , which is connected to the line *A* and to the centre point of transformer T_1 .

To obtain equal voltages on each phase of the motor, each transformer must have the same number of turns. The turns on transformer T_2 , between the tapping (*J*)—to which the centre of transformer T_1 is connected—and the end (*D*) of the winding must be $0.866 (= \frac{1}{2}\sqrt{3})$ of

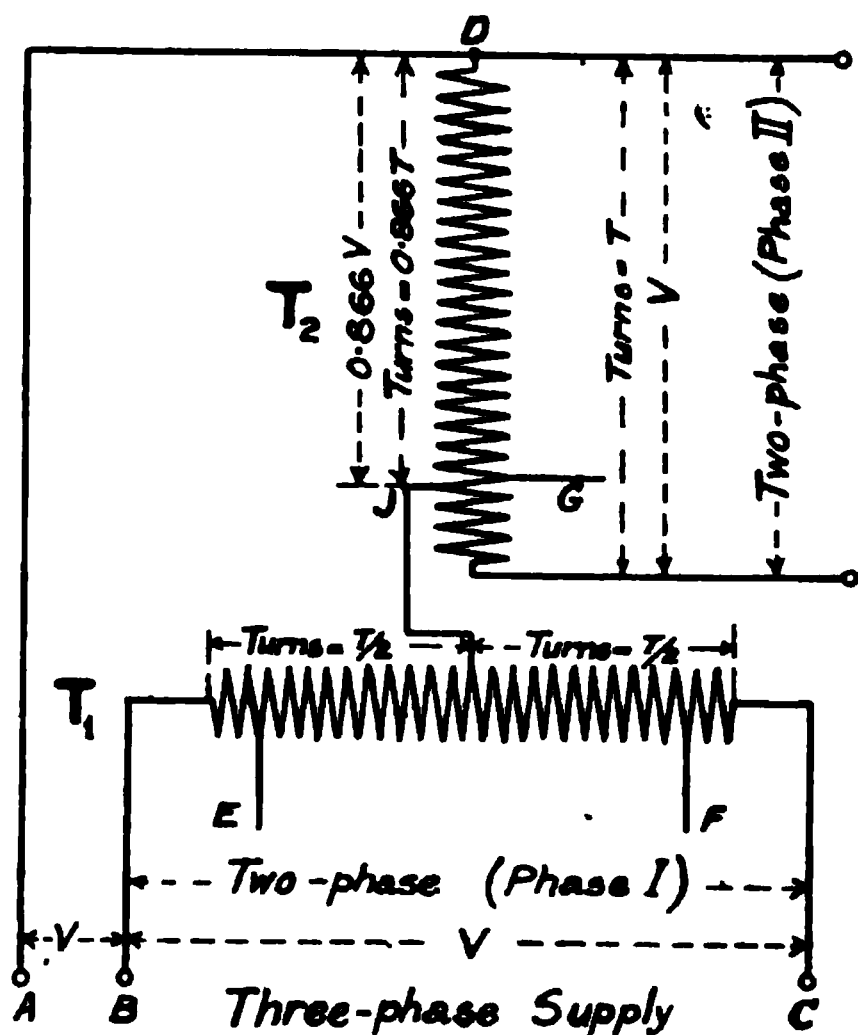


FIG. 216.—Connections of Three-phase/Two-phase Auto-transformers.

the turns on transformer T_1 , while the turns between tapping *G* and the end *D* must be 0.75 of the turns on transformer T_1 (i.e. the same as the turns between tapplings *E* and *F*).

The switches required to effect the various combinations between the motors, the rheostat, and the auto-transformers for this method of four-speed cascade-parallel control (in which the speeds are in the ratio of $1 : 1.33 : 2 : 2.66$) will therefore include the following:—

Pole-changing switches for primary and secondary motors.

Switches for connecting the auto-transformers to the lines and the motors.

Regrouping switch for secondary motor.

Change-over switch.

The change-over switch will require to have four positions, the combinations for each position being as follows:—

- (a) *8-pole cascade*—three-phase slip-rings of primary motor connected to regrouping switch of secondary motor; three-phase slip-rings of secondary motor connected to rheostat.
- (b) *8-pole parallel*—stator winding of secondary motor connected in parallel with stator winding of primary motor; three-phase slip-rings of primary motor connected in parallel with those of secondary motor.
- (c) *6-pole cascade*—two-phase slip-rings of primary motor connected to regrouping switch of secondary motor; two-phase slip-rings of secondary motor connected to rheostat.
- (d) *6-pole parallel*—stator winding of secondary motor connected in parallel with stator winding of primary motor; two-phase slip-rings of primary motor connected in parallel with those of secondary motor.

It is possible, however, to combine the change-over switch with the regrouping and the pole-changing switches of the secondary motor, thereby considerably simplifying the control apparatus. The switches for connecting the auto-transformers in circuit may be combined in a similar manner with the pole-changing switch of the primary motor.

For example, in the 2600-H.P. express passenger locomotives built by the Società Italiana Westinghouse for the Italian State Railways (see Chapter XVII, p. 398)—where the above method of control is adopted—the whole of the combinations for the secondary motor are performed by two drum-type controllers, the shafts of which are geared together and operated from a pair of double-acting pneumatic cylinders (see Fig. 88, p. 115).

Thus, although there are a large number of connections to be made, the master controller and the control circuit connections are quite simple.

TYPICAL CONTROL APPARATUS FOR MULTI-SPEED METHODS OF CONTROL

Control apparatus for multi-speed three-phase equipments has been developed almost exclusively for use on electric locomotives. Notwithstanding the apparent complexity of the combinations to be effected by this apparatus in some of the multi-speed methods of control (*e.g.* the two-speed and four-speed cascade-parallel methods), the control equipment of many three-phase locomotives is characterised by its general simplicity and the small number of parts.

This simplification of the control equipment is obtained by the adoption of high-voltage motors and automatic liquid rheostats, together with the use of compressed air for performing the principal operations of the control apparatus.

Therefore no switches are required to break heavy currents, and by confining the interruption of the main primary circuits to the reverser, the pole-changing, change-over, and regrouping switches have to be designed with reference to current-carrying capacity and insulation only. Consequently these latter switches may be of the controller or drum type,* which type of switch, for high-voltage equipments, has obvious advantages over a number of separate contactors.

Of course, with low-voltage motors—supplied from a phase-converter or transformer—some of the above switches (*e.g.* the reverser) will be required to break heavy currents, for which purpose contactors would be desirable. The pole-changing, change-over, and regrouping switches, however, may be of the controller type.†

Automatic Liquid Rheostat.—The most interesting portion of the control equipment is the automatic liquid rheostat. The liquid rheostat was first applied to railway purposes (in about 1901) by Ganz & Co. in connection with the equipment of the Valtellina line of the Italian State Railways.‡ The experience obtained on this line proved that a liquid

* With a line voltage of 3000 volts, the full load current of a 1000-H.P. three-phase railway motor is approximately 160 amperes. This current can be carried continuously by a controller finger and segment $1\frac{1}{2}$ in. wide.

† Refer to Fig. 187, p. 218, for an example of a controller of large current-carrying capacity.

‡ See *The Electrician*, vol. 51, p. 19, for a description of the original equipment on this line.

rheostat possesses several advantages for the control of three-phase motors on the cascade system. Improvements have been introduced into later rheostats by Ganz & Co. and the Società Italiana Westinghouse, so that at the present day the liquid rheostat has a wide application for three-phase locomotives.

The **general features of liquid rheostats** for three-phase railway motors are :--

A number of electrodes, of iron plate, are suspended in the upper part of a tank into which a solution of carbonate of soda can be ad-

FIG. 217.—Società Italiana Westinghouse Automatic Liquid Rheostat for Three-phase Electric Locomotives.

mitted from a storage tank (at a lower level) by means of compressed air which is supplied to the latter tank through suitable valves. The rate at which the liquid rises between the electrodes (and therefore the rate at which the resistance is cut out) is governed by the air pressure in the storage tank, which pressure is regulated by a valve or combination of valves operated by the motor current. When the liquid has risen to a certain height, the electrodes are automatically short-circuited by a special switch. In the more recent rheostats, provision is made for an efficient circulation and cooling of the liquid in order to reduce evaporation. Rheostats of this type have been standardised for all locomotive equipments on the Italian State Railways, and have recently been adopted by the Westinghouse Co. for controlling the three-phase motors on the Norfolk and Western split-phase locomotives, notwithstanding

that the grid type of rheostat is the accepted standard for all railway and industrial purposes in America.

The latest type of rheostat constructed by the **Società Italiana Westinghouse** for the express passenger locomotives (type F.S. 330, class 2-6-2) of the Italian State Railways is illustrated in Fig. 217, while Fig. 218 illustrates the type of rheostat which has been developed by the Westinghouse Co. for the Norfolk and Western locomotives.

Referring to Fig. 217, the upper portion of the corrugated tank *A* contains the electrodes (the terminals of which are visible in the illus-

FIG. 218.—Westinghouse Liquid Rheostat for Three-phase Locomotive.

tration), while the lower portion of the tank forms the reservoir for a solution of sodium carbonate.* This portion of the tank communicates, by means of the pipe *B*, with the pneumatic head-piece *C*, which contains the valves for controlling the supply of compressed air to the pipe *B* and the reservoir. The valves performing this function are two in number, one for admission and one for exhaust, and are of the pneumatic-relay type. They are controlled by means of electrically-operated pilot valves, which are energised from an automatic regulator, to be referred to later. These pilot valves, of which two are visible in Fig. 217, are of the standard Westinghouse type.

When the liquid rises in the electrode chamber to a predetermined height, the electrodes are automatically short-circuited by the switch *D*.

* The rheostat illustrated in Fig. 217 is designed for controlling two 1300-H.P. motors. The reservoir contains 1550 lb. of fluid.

This switch is operated by compressed air, and the valve controlling it is actuated by a float in the electrode chamber. At the same time as the electrodes are short-circuited, two other switches are operated. One of these switches controls a signal lamp in the driving compartment of the locomotive—thereby indicating to the driver that the rheostat is short-circuited—while the other switch opens the circuit of the motor driving the circulating pump.

When the rheostat is in operation, a centrifugal pump—located in the reservoir—maintains an efficient circulation of the liquid between the reservoir and the electrode-chamber, thereby preventing local heating and evaporation of the liquid. The pump is driven by a three-phase induction motor *E* (with squirrel-cage rotor), which is automatically controlled by a switch *F*, so that the motor is only in operation while power is being absorbed in the rheostat.

The automatic regulator (which is shown at *G* in Fig. 217) is designed to regulate the resistance of the rheostat for a *constant watt-input to the motors*.* In construction, the regulator is similar to a small two-pole induction regulator; the stator consists of a laminated core, with a two-pole winding connected in series with the earthed phase of the motors; the rotor consists of a double T-shaped laminated core, with a shunt winding excited from the transformer supplying the control circuits. The torque between the stator and rotor is, approximately, proportional to the watts input to the motors and is balanced by a spring, the tension of which can be regulated by the driver (from the master controller) so as to predetermine the power input to the locomotive.

The motion of the rotor is restricted between two stops, adjacent to which are contacts connected in series with the magnet coils of the pilot valves which control the admission of air to the reservoir tank.

In starting, the driver applies a tension to the spring—by means of a handle on the master controller—which rotates the rotor so as to energise the pilot valve admitting air to the reservoir. The liquid then rises in the electrode chamber, thereby increasing the electrical input to the motors and, consequently, the torque between the stator and rotor of the regulator. When this torque just balances the tension of the spring, the rotor assumes its neutral position and interrupts the circuit of the pilot valve. If the motor input increases, the torque of the rotor exceeds that of the spring, and the pilot valve exhausting the air from the reservoir is energised, thereby lowering the level of the liquid in the electrode chamber and reducing the motor input.

In order to obtain a constant input to the motors when they are connected in cascade and also in parallel, the stator winding of the regulator is wound in two sections, which are connected in series for the cascade connection of the motors and in parallel for the parallel connection of the motors, these groupings being effected by means of fingers and segments on the change-over switch.

Reverser.—In equipments with high-voltage motors, the reverser generally fulfils the combined functions of a reversing and circuit-

* In the rheostats supplied with the earlier (1909) freight locomotives (type F.S. 050, class 0-10-0) the regulator was designed to regulate for constant current input. The present type of regulator was developed so that the acceleration of locomotive should not be influenced by variations of the line voltage.

breaking switch. An illustration of a reverser of this type, which is standard for all the equipments on the Italian State Railways, is shown in Fig. 219. The switch consists of six copper plungers (or rods) fixed by insulators to a circular cross-head, which can be raised, lowered, and rotated through an angle of 60 degrees. When the cross-head is raised, the plungers fit into corresponding sockets contained in long vertical (porcelain) tubular insulators fixed to the upper portion of the case.

The phases of the supply and the motors are connected to the six sockets, while the six plungers are cross-connected in the manner shown in Fig. 220, A. This diagram shows the position of the cross-head corresponding to, say, forward running of the locomotive, and when the reverser is closed the connections between the supply and motors are as shown in Fig. 220, B. When the cross-head is rotated through an angle of 60 degrees, the connections between two of the phases of the supply and the motors are interchanged (see Fig. 220, C), thereby reversing the direction of motion of the locomotive.

All the operations of closing, opening, and reversing are performed by compressed air, the cylinders for reversing (i.e. rotating the cross-head through 60 degrees) being shown on the top of the case.

FIG. 219.—Combined Reversing and Circuit-breaking Switch for 3000-volt Equipments.

The switch has a long break (about 10 in.) and, since each phase is interrupted in two places simultaneously, the voltage broken at each plunger and contact, with normal line voltage (3000 volts), is $\left(\frac{1}{2} \times \frac{3000}{\sqrt{3}} = \right)$ 866 volts.

This combined reversing and circuit-breaking switch is used for interrupting the circuit during normal operation, but the equipment is, of course, protected against overload by means of an automatic oil-switch.

Pole-changing switches.—In control equipments for changeable-pole control, the pole-changing switches are usually in the form of drum-type controllers operated pneumatically from a suitable master controller.* These switches are not intended for breaking the circuit, which operation is performed by means of either a reverser of the above type, or a double-pole oil-switch combined with the pole-changing switch. The latter method is adopted for four-speed changeable-pole equipments, as it

* For multiple-unit operation, the admission of air to the pneumatic cylinders would be performed by electrically controlled pilot valves, similar to those adopted in the Westinghouse electro-pneumatic control system.

enables the two pole-changing windings of the motor to be used either in parallel or singly. Separate pole-changing and circuit-breaking switches are used for each pole-changing winding.

A diagram of the connections and development for the standard type of pole-changing switch is shown in Fig. 221.

Regrouping and change-over switches for cascade control.—The connections for these switches have been considered above. It may be observed that, for two-speed cascade-parallel equipments, the change-over switch may be combined with the regrouping switch when the latter is of the controller type. Hence, with the usual method of pneumatic

Pneumatic Cylinders

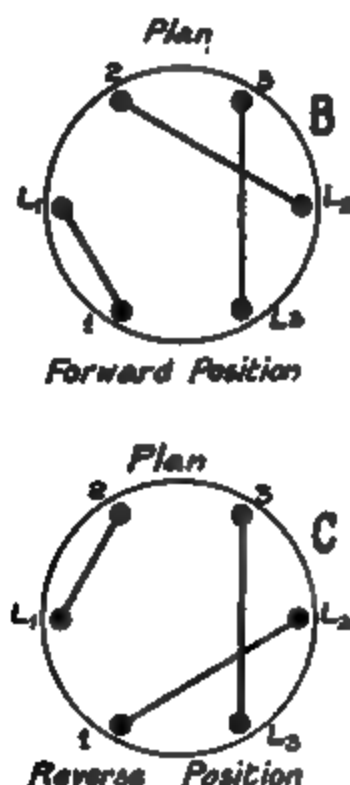


FIG. 220.—Reversing Switch for Three-phase Motors.

operation, only one double-acting pneumatic cylinder is required for effecting the cascade and parallel combinations of the motors and rheostat.

Master controller.—In multi-speed control equipments for three-phase locomotives, the master controller possesses several features of interest, since the functions of the controller are of a different nature to those which obtain in continuous-current and single-phase equipments. For example, the driver must be capable of controlling (1) the direction of motion of the locomotive, (2) the speed at which it is to operate, (3) the acceleration during starting, and (4) the retardation during regenerative braking. Moreover, in many three-phase locomotives, the operation of the various switches is carried out entirely by means of compressed air. In these cases, therefore, the master controller becomes a combination of valves and contains no electrical circuits.

For multiple-unit operation of the locomotives the pneumatic cylinders of the various switches must be controlled by electro-magnetic pilot valves, so that, for these cases, the master controller will follow the general lines of its prototypes for continuous-current and single-phase electro-pneumatic equipments.

Thus, the master controller must energise the magnets of the pilot valves controlling the reversing, the pole-changing, and other switches, and must also set the automatic regulator of the rheostat for the required acceleration. It is possible to arrange for these operations to be performed by two handles, viz. one handle controlling the speed and the direction of motion, and another handle controlling the acceleration. On the other hand, with "all-pneumatic" control equipments, three handles will be required, as the valves controlling the pneumatic

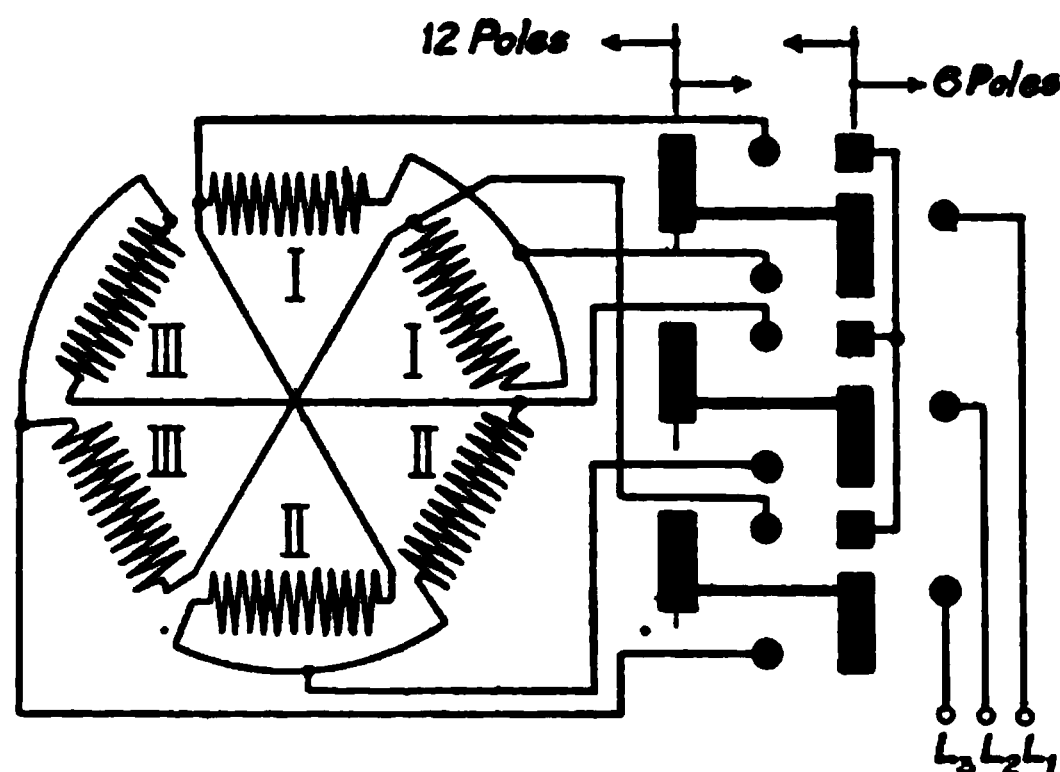


FIG. 221.—Connections and Development of Pole-changing Switch.

cylinders of the various switches must be operated directly from the controller.

In considering master controllers in detail, we have to distinguish between those for electro-pneumatic control, all-pneumatic control, and combined pneumatic-hand control. Controllers for electro-pneumatic control have been developed by the Società Italiana Westinghouse and the Westinghouse Co., while those for the pneumatic systems of control have been developed by Ganz & Co.* and Brown, Boveri & Co.

The simplest of the pneumatic controllers is that developed by Brown, Boveri & Co. for the two-speed locomotives operating through the Simplon Tunnel. In these locomotives the motors are of the changeable-pole type, and have wound rotors with separate windings and slip-rings for each set of poles. The rheostats, of which there is one for each rotor winding, are of the wire type with face-plate switches manually operated.

The master controller is illustrated in Fig. 222. The central hand-wheel controls the valve operating the main switch and also operates the switches of the rheostats by means of bevel and chain gearing. The two side handles operate the valves controlling, respectively, the reverser

* For description and illustrations of Ganz pneumatic controllers see *L'Éclairage Électrique*, vol. 43, p. 487.

FIG. 222.—Brown, Boveri Master Controller for combined Hand and Pneumatic Control.

FIG. 223.—Westinghouse Master Controller for Electric Locomotives (Electro-pneumatic Control).

and the pole-changing switch. These handles are interlocked with each other and the central handle, so that the operations can only be carried out in the correct manner.

In the electro-pneumatic systems of control, the control circuit is supplied with either single-phase alternating current—at from 80 to 100 volts—or continuous current at a low voltage (obtained from accumulators). Hence the master controller will only have to handle small currents at low voltage, so that no arc-suppressing devices will be required.

An illustration of a Westinghouse master controller (for the Norfolk and Western locomotives described in Chapter XVII) is shown in Fig. 223. The controller is arranged for the control of a double locomotive on the multiple-unit system, each half of the double locomotive being equipped with four 410-H.P., 750-volt, three-phase, changeable-pole motors. Three handles are provided—one for operating the reverser, and the other two for controlling, respectively, the contactors forming the pole-changing switch and the valve magnets of the liquid rheostat.

CHAPTER XII

THE CONTROL OF CONTINUOUS-CURRENT AND ALTERNATING-CURRENT MOTORS FOR REGENERATIVE BRAKING

IN Chapter III we have shown that the energy output from the motors of an electric train, operating on a level track, is expended in (1) accelerating the train, and (2) overcoming the resistances to motion. When the train is running at constant speed, the kinetic energy which it possesses is equal to the energy expended in acceleration. During coasting a portion of this energy is utilised for propelling the train (*i.e.* in doing work against train resistance), and the rate at which this conversion of energy takes place determines the retardation. Hence, coasting may be considered as a form of **mechanical regenerative braking** or recuperation of energy. Generally, the greater the ratio of the coasting period to the total running period the lower will be the energy consumption; but prolonged coasting will result in a low schedule speed, and will require an increase in the acceleration if the original schedule speed is to be maintained. The increase in the acceleration will usually involve the use of larger motors, so that the gain in the energy consumption may be neutralised by the increased train weight and the additional cost of the equipment.* With modern urban and suburban traffic conditions, it is only possible to allow a coasting period of from 20 per cent. to 50 per cent. of the total running period,† and, consequently, a large percentage of the acceleration energy has to be wasted in the brakes.

By suitably **grading the track** the kinetic energy of the train may also be utilised in doing work against gravity. When the train is brought to rest it will, therefore, possess a certain amount of potential energy which can be utilised for the purpose of acceleration during the descent of the train to the level. This form of mechanical regenerative braking is adopted on the London tube railways,‡ the tracks being graded in the manner shown in Fig. 224. As far as the conditions of construction will permit, the station platforms are arranged at the same level. The tracks between the stations are constructed with a 1 in 60 (1·66 per cent.) *up* gradient on the entering side; a 1 in 30 (3·3

* For other limitations to the acceleration see p. 11.

† In this connection see *Electric Railway Journal*, vol. 45, p. 705, where values are given for the duration of the coasting periods on a number of city railways.

The matter is discussed in detail in Chapter XIX.

‡ Regenerative braking—whether mechanical (by means of gradients) or electrical—is an important feature in tube railways, where dust should be specially avoided. In the London tube railways, the brake-block wear is reduced by more than 50 per cent. by the adoption of a graded track in contrast to a level track.

per cent.) *down* gradient on the leaving side, and a level stretch between the gradients.* The lengths of the gradients are arranged so that power is cut off from the motors when the train is on the level. Mechanical regenerative braking occurs while the train is ascending the 1 in 60 gradient, and the final stage in the braking is performed by the application of the mechanical brakes as the train enters the station.

In the case of the Central London Railway the gradients result in a recuperation of 14 watt hours per ton mile, which corresponds to about one-third of the energy consumption of a seven-car train operating at a schedule speed of 14 ml.p.h.†

The total economy, however, is not simply represented by the decreased energy consumption of the train, because the service can be run with smaller equipments than a similar service on a level track. Economies will, therefore, be effected in the interest and depreciation charges on the equipments and the rolling stock. Moreover, the improvement in the load-factor at the power house, due to the lower peak

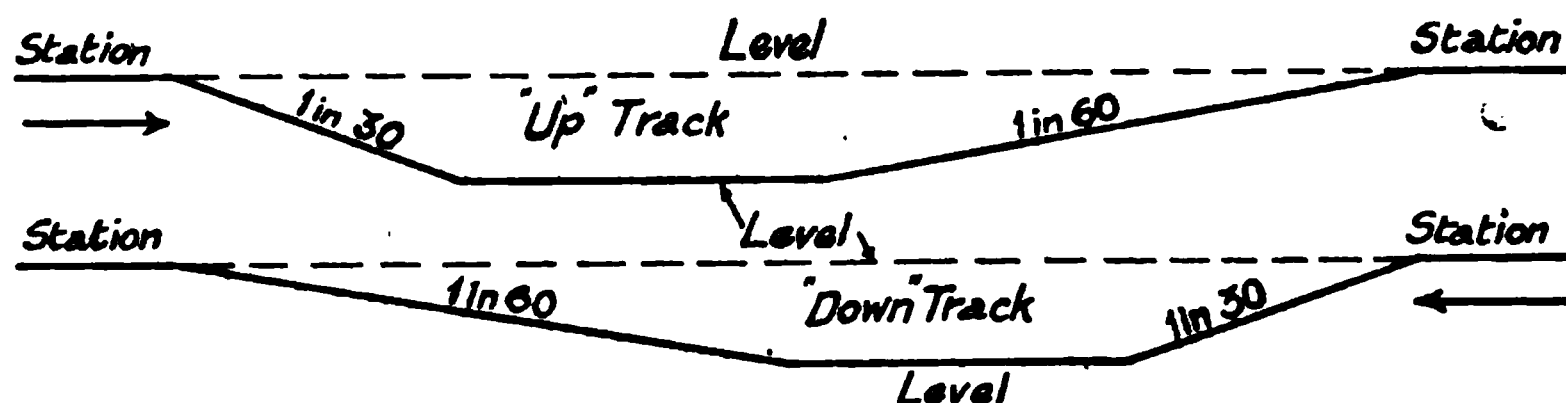


FIG. 224.—Grading of Track on London Tube Railways.

load, enables the generating plant to be operated at a high average efficiency, which is conducive to low generating costs.

Although the above graded track construction is quite practicable for tube railways, it is scarcely practicable for surface railways. Therefore it will be necessary to confine our attention to surface lines, and for the present we shall consider the track to be level. Hence, if greater reductions are to be effected in the energy consumption by means of regenerative braking, the electrical equipment must be utilised for this purpose. The motors must, therefore, be capable of operating as generators during the period of retardation, and the power generated in the machines must be returned to the supply system.

The methods of converting continuous-current series motors into generators for braking purposes have been discussed in Chapter VIII (see p. 147). There are, however, important differences between *electric braking* and *electric regenerative braking*. For instance, with electric braking the voltage generated in the motors is not of considerable importance, as the braking effect can be regulated by the rheostats. On

* The reason for the difference in the *up* and *down* gradients is, that a gradient of 1 in 30 against a train would be very disadvantageous in the case of a signal stop.

† A complete analysis of the energy consumption on the Central London Railway has been given by Messrs. Parshall, Parry, & Casson in a paper on "The Central London Railway" published in *Traction and Transmission*, August, September, October, 1903. See also *Proceedings of the Institution of Mechanical Engineers*, 1912, p. 939.

The average energy consumption (input from the conductor rail) for a seven-car train, weighing 120 tons, was found to be 43 watt-hours per ton mile when this train was running the service at a schedule speed of 14 ml.p.h.

the other hand, with regenerative braking the voltage generated in the motors must at all times exceed the supply voltage by an amount which is equal to the voltage drop (due to resistance) in the machines and connections. Moreover, the generated voltage must be maintained at this value throughout the period of recuperation. Obviously the latter conditions can only be satisfied by having the field windings of the machines either separately excited or shunt excited, series excitation being entirely inadmissible.

Hence the series motor, which possesses the most suitable characteristics for propulsive purposes, does not possess suitable features for regenerative braking. Recuperation can be obtained, however, by separately exciting the field winding and inserting a booster in the armature circuit, as explained below; but the power required to drive the booster and the excitation sets must be generated in the main motors before recuperation can take place. In many cases the increased cost of the additional equipment necessary to obtain regenerative braking with series motors, combined with the increase in the maintenance costs, and the increase in the weight of the equipment, may entirely off-set the economy in the energy consumption.

On the other hand, the shunt motor possesses features which appear to be ideal for regenerative purposes. Thus separate excitation of the field winding is unnecessary; no changes are required in the connections, since the machine is converted from a motor into a generator by simply strengthening the exciting current, and the current returned to the supply system is under control at all times.

In practice, however, regenerative braking with continuous-current shunt machines cannot be carried out with such simplicity. For instance the motors, when operating as generators, must be provided with a differential series winding in order that the load may be divided equally between two or more machines connected in parallel, and also to prevent damage to the equipment due to a sudden increase in the (shunt) exciting current. Moreover, precautions must be taken to prevent an excessive voltage being generated in the machines.*

If recuperation is required over a wide range of speeds, it will be necessary to adopt series-parallel control. The application of this system of control to shunt machines introduces difficulties which are not associated with the series-parallel control of series motors. The principal difficulties are connected with the transition steps, the steps for the transition from series to parallel not being suitable for the transition from parallel to series.

These difficulties are not insurmountable, but they tend to complicate the control apparatus.

Several attempts have been made in this country to introduce **regenerative braking on tramways**, but for various reasons they have not been commercially successful.†

* These precautions are necessary for the following reason. Suppose a car to be descending a gradient with the motors returning current to the supply system. If the main current were interrupted—due to, say, the circuit-breaker opening—the voltage generated in the motors would not be restricted to the normal value (which is in the neighbourhood of the line voltage) but, with the increasing speed of the car, would build up to an excessive value.

† A large amount of development in tramcar equipments for regenerative control has been done by the Brush Electrical Engineering Co. (under Raworth's Patents)

Experience with regenerative equipments on tramways has shown that on level routes the energy consumption is about 10 per cent. lower than that of a standard (series motor) equipment, the operating conditions being similar in each case. With undulating routes the saving may be of the order of 20 per cent. On the other hand, the equipments for regenerative control are more costly than standard series-motor equipments, while the cost of maintenance for the former equipments will generally exceed that for standard equipments. Moreover, devices are required at the generating station to prevent the generators being supplied with current from the car motors.

Thus, in many cases, the total running costs for cars with regenerative equipments will not differ appreciably from those for cars with standard equipments. It is apparent that, in these cases, very little advantage is gained by the substitution of regenerative equipments for standard equipments.

The above conditions apply, to some extent, to regenerative equipments for urban and suburban railways, but in these cases there are greater possibilities for regenerative control on account of the higher efficiency of the equipment and the large amount of kinetic energy available. It is desirable, however, that the "series" characteristics of the motors be retained for propulsive purposes, in order to enable a high acceleration to be obtained without the use of heavy motors. At the present time the introduction of regenerative control into equipments for urban and suburban railways is only in the experimental stage. A multiple-unit train, equipped with series motors and regenerative control, is in service on the Metropolitan Railway, Paris, and the results of tests indicate that a saving of 20 per cent. in the energy consumption (in comparison with standard equipments) can be obtained.*

With main-line railways having long and heavy gradients—more especially those on which the traffic consists principally of freight trains—the conditions for regenerative braking are very favourable, and not only can considerable economies be effected in the energy consumption, but heavier trains can be handled on the down gradients at considerably higher speeds than would be permissible with mechanical braking.

A striking example of the advantages of electric regenerative

and the Johnson Lundell Co. In the Raworth regenerative system, standard traction motors were adopted and were provided with compound field windings. The motors were operated as shunt machines (with series-parallel control) during acceleration and braking, the series winding being used for parallel operation and also for rheostatic braking. Details of the system of control, together with test results, will be found in a paper by Mr. A. Raworth on "The Regenerative Control of Electric Tramcars" (*Journal of the Institution of Electrical Engineers*, vol. 38, p. 374).

* The motors for the Johnson-Lundell system were special machines with laminated magnetic circuit, double armature windings, and compound field windings; they were operated as series machines during acceleration, and as differential compound machines during regenerative braking; the change in the connections being effected by a special electrically-operated controller known as a "field changer." The control during acceleration and regenerative braking was on the double series-parallel system. Complete data of the design of the motors and the method of control will be found in "Electric Motors" (Hobart), 2nd edition, p. 252.

* See p. 268 for details of the method of control.

A description of the equipment, together with curves of energy consumption, will be found in the *Electric Railway Journal*, vol. 43, p. 302.

braking on a railway with heavy gradients is found on the Giovi-Genoa lines of the Italian State Railways.* With electric traction, the capacity of the lines has been trebled, due to the heavier trains which can be run on the down gradients, and the higher speeds permissible with electric braking. The running costs have been found to be only about 75 per cent. of those when the lines were operated with steam locomotives, although the plant of the generating station is not fully utilised. These low costs are the result of electric recuperation of energy on the down gradients, the recuperated energy being of the order of from 60 per cent. to 80 per cent. of the energy consumption for the up journey with the same train.† Considerable saving is also effected in the brake shoes, wheel tyres, and rails, as the mechanical brakes are only used for "slow-downs" and stops.

Other railways with heavy gradients, on which electric regenerative braking is adopted, are the Cascade Tunnel of the Great Northern Railway, U.S.A.‡; the Norfolk and Western Railway (West Virginia, U.S.A.)§; the Puget Sound lines of the Chicago, Milwaukee, and St. Paul Railway||; and the Villefranche-Ile lines of the Midi Railway (France). In all these cases the electrical equipment has been designed with special reference to regenerative braking. The equipments for the Chicago, Milwaukee, and St. Paul Railway have continuous-current series motors, while those for the Midi Railway have single-phase commutator motors: in the other cases the equipments have three-phase induction motors.

CONTROL SYSTEMS FOR ELECTRIC REGENERATIVE BRAKING ON RAILWAYS

I. Regenerative Control Systems for Three-phase Motors.—The simplest control system for regenerative braking is obtained by the adoption of three-phase induction motors with wound rotors and automatic liquid rheostats. The property of a three-phase induction motor operating as an asynchronous generator at speeds above synchronism is well known, and this property forms the essential feature in the control of the motor for regenerative braking. Now, when the machine is operating as a motor at constant supply voltage and frequency, the slip, with constant rotor resistance, is practically proportional to the torque, while for constant torque the slip varies approximately as the rotor resistance (see p. 102). It can be shown that similar relations exist

* For a description of this electrification see *Tramway and Railway World*, vol. 27, p. 345; vol. 35, p. 184.

† In all cases of regenerative control, the efficiency of the equipment has an important bearing on the economical results. It is only with the use of large gearless three-phase motors that results of the above order can be obtained.

‡ For data of this electrification see a paper by Dr. Cary T. Hutchinson on "The Electric System of the Great Northern Railway" (*Transactions of the American Institute of Electrical Engineers*, vol. 28, p. 1281).

§ A complete description of this electrification will be found in the *Tramway and Railway World*, vol. 38, p. 9, and the *Electric Railway Journal*, vol. 45, p. 1058.

|| Data of the gradients, traffic, and system of electrification for this railway will be found in the *General Electric Review*, vol. 18, pp. 5, 600; the *Electric Railway Journal*, vol. 45, p. 1072, and the *Tramway and Railway World*, vol. 37, p. 87.

when the machine is operating as a generator, the torque in this case being *supplied* to the rotor and the slip being negative.*

Therefore, in order to obtain regenerative braking on level track, it will be necessary to adopt multi-speed control. Considering the two-speed cascade-parallel system of control, if the train is running with the motors connected in parallel, regenerative braking can only be obtained by connecting the motors in cascade, and the braking ceases when the speed of the train reaches the cascade-synchronous speed of the combination. The control of the retardation during braking must be effected by regulating the resistance in the rotor circuit of the secondary motor. This, of course, involves a loss of energy. Hence it is apparent that the economy obtainable from regenerative control on level track will not be very great, although, by the adoption of four-speed equipments, the loss in the rheostats can be reduced. Against these disadvantages we have the great advantages of simplicity in the control and the absence of additional control apparatus.

With trains operating on gradients the economy obtainable from regenerative braking will be very considerable, since, under normal conditions, it is unnecessary to insert resistance in the rotor circuit.

The speed at which the train descends the gradient will be constant (assuming constant frequency and voltage), and will be practically independent of the gradient and the weight of the train; while the energy returned to the supply system will equal the work done by gravity, less the energy expended against train resistance and the losses in the motors and equipment. Thus the load on the motors, when regenerating, is determined by the weight of the train and the gradient.

It is apparent that with the rotors short-circuited, light trains will descend at practically the same speed as heavy trains, but flexibility in this direction can be obtained, without sacrifice of efficiency, by the use of multi-speed equipments. Of course, by inserting resistance in the rotor circuit, the light trains may be taken down the gradient at any speed desired, but this involves a loss of energy in the rotor rheostats.

When two or more three-phase locomotives have to be coupled together for the purpose of handling a heavy train down a gradient, it is desirable that the locomotives should share the load equally in spite of any differences in the diameters of the driving wheels. This condition is easily obtained with equipments provided with automatic liquid rheostats. The rheostats on the locomotive with the largest driving wheels are short-circuited; while the rheostats on the other locomotives are adjusted (from the driving master controller) to maintain a load on these locomotives equal to that on the former locomotive.

It should be pointed out that, on railways which are supplied with electrical energy from a separate generating station, conditions may occur during regenerative braking on steep gradients when the recuperated energy is greater than the energy output from the generators. These conditions would be dangerous to the plant at the generating station, and also to the trains descending gradients. Hence provision must

* If n = speed of rotor in r.p.m., and n_s = synchronous speed in r.p.m., the slip (as motor) = $\frac{n_s - n}{n_s} = 1 - \frac{n}{n_s}$, and the negative slip (as generator) = $\frac{n - n_s}{n_s} = \frac{n}{n_s} - 1$.

be made for dissipating the excess of energy in loading rheostats, and usually these are of the water type.*

II. Regenerative Control Systems for Continuous-current Series Motors.—A system of regenerative control for multiple-unit equipments has been developed by the Jeumont Co. (Ateliers de Constructions Électriques du Nord et de l'Est), and has been tested with satisfactory results on the Metropolitan Railway, Paris.

The system involves the use of a booster-exciter set, the booster being used for starting and speed regulation as well as for regenerative braking. Thus starting rheostats are dispensed with, and an economical method of speed control is obtained.

The booster and the driving motor are four-pole machines, with commutating poles and a common frame. The armatures of these machines are mounted on a common shaft which is carried in ball bearings.

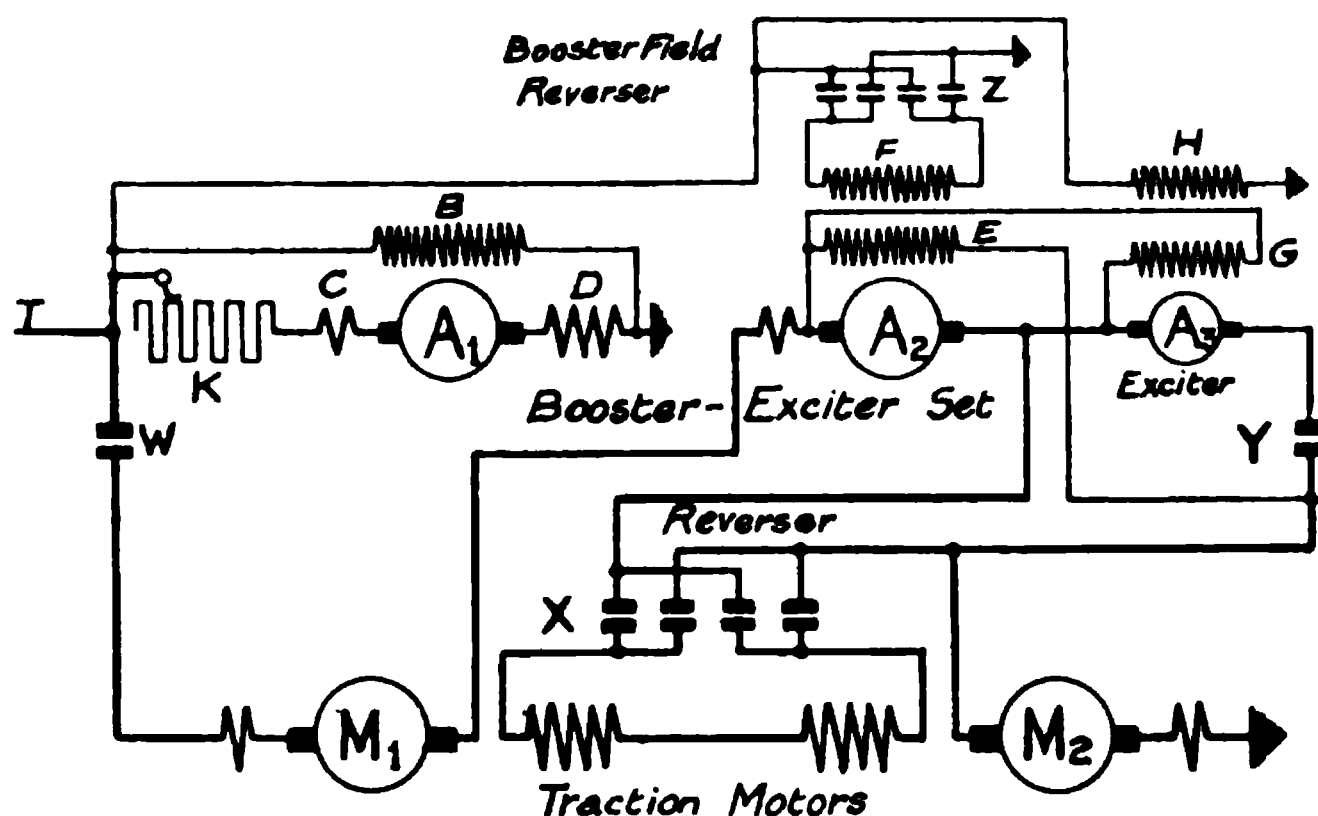


FIG. 225.—Diagram of Connections of Jeumont System of Regenerative Control for Continuous-current Railway Motors.

The exciter armature is fixed to an extension of this shaft, while the exciter magnet frame is bolted to one of the frame heads of the booster frame. In this manner a compact set, with very low mechanical losses, is obtained. The booster and exciter are each provided with two shunt windings, while the driving motor is provided with a compound field-winding.

The general scheme of connections is shown diagrammatically in Fig. 225. The armatures and field windings of the two traction motors M_1 , M_2 are connected permanently in series with the armature A_2 of the booster, the field windings of the traction motors being connected to a set of contactors X , which fulfil the functions of a reverser and a circuit-breaking switch. The exciter armature A_3 can be connected in parallel with the field windings of the traction motors by means of the contactor Y .

* For particulars of the regenerative loading rheostats for the Giovi lines, see *The Engineer*, vol. 116, p. 297.

These loading rheostats are unnecessary in the case of a large generating station supplying industrial works as well as railways.

The field windings of the booster are shown at E , F , the winding F being separately excited through a reversing switch Z , while the winding E is self-excited and connected across the armatures of the booster and exciter. The field windings of the exciter are shown at G , H , of which the winding H is separately excited and the winding G is excited from the booster armature.

The motor of the booster-exciter set is started by an automatic starting switch K . The armature and field windings of the motor are shown, in Fig. 225, at A_1 , B , D respectively, the commutating-pole winding being shown at C .

The traction motors are started in the following manner:—

(1) The reverser X is closed to correspond to the required direction of motion.

(2) The field winding F of the booster is excited in a direction such that the E.M.F. generated in the booster-armature opposes the supply voltage, the excitation being adjusted so that on closing the contactor W , the normal accelerating current will pass through the motors.

(3) The contactor W is closed, and the traction motors are accelerated by decreasing the excitation of the booster. During this process, the booster armature A_2 is acting as a motor, while the motor armature A_1 is acting as a generator and returning energy to the supply system. When the excitation supplied by the field winding F is zero, the voltage generated in the booster-armature will be practically zero, and each traction motor will receive approximately one-half of the supply voltage. This condition corresponds to the "full series" position in series-parallel control.

(4) The field winding F is now excited in the reverse direction, and the voltage of the booster-armature A_2 is built up—in the same direction as the supply voltage—until each motor receives normal (line) voltage. During this process the booster-armature is acting as a generator.

By suitably arranging the control of the exciting winding F , the accelerating current can be maintained constant, and a uniform acceleration obtained.

Regenerative braking is obtained by closing the contactor Y and controlling the excitation of the booster in the reverse manner to that for acceleration. During regenerative braking, the field windings of the exciter will act either differentially or cumulatively, according to the direction of the voltage generated in the booster.

Thus, in braking from full speed (when the booster is giving its full voltage) the winding G opposes the winding H , and the voltage generated in the exciter armature is small. As the braking proceeds, the voltage generated in the booster-armature decreases, thereby increasing the excitation on the exciter, and increasing the current in the field windings of the traction motors. Finally, the excitation of the booster is reversed, so that its voltage opposes the supply voltage; while, at the same time, the field windings of the exciter act cumulatively and increase the voltage generated in the exciter.

The use of two shunt windings on the booster enables a gradual variation of the voltage generated in the armature to be obtained with a small number of steps in the field rheostat, while the two shunt windings on the exciter produce automatic control of the excitation of the traction motors, the excitation varying approximately inversely as the speed of the latter.

The weight of the booster-exciter set, together with the controlling apparatus suitable for two 175-H.P. traction motors, is 4070 lb., but as the regenerative control eliminates the starting rheostats, the net increase in the weight of the regenerative equipment is 3080 lb.

In some tests * on the Paris Metropolitan Railway, under service conditions, the regenerative equipment showed an energy consumption 20 per cent. lower than that of a standard equipment (the respective figures being 48 and 60 watt hours per ton mile); while, during braking, the energy returned to the supply system reached 30 per cent. of the energy used in acceleration.

III. Regenerative Control Systems for Single-phase Commutator Motors.—The problem of obtaining regenerative braking from single-phase motors presents difficulties which are considerably greater than those discussed above in connection with continuous-current equipments.

Electric (or rheostatic) braking can be obtained with single-phase series motors in the same manner as with continuous-current series motors, viz. by operating the motor as a self-excited series generator and loading it on rheostats.

When regenerative braking is required, certain conditions must be satisfied. These conditions are practically the same as those given above in connection with continuous-current equipments, but with single-phase equipments it is necessary to consider the *power-factor of the regenerated current*. Obviously, there is no advantage in returning wattless current to the supply system; therefore all successful schemes for regenerative braking must aim at a high power-factor during recuperation, and it is in the attainment of this high power-factor that the principal difficulties are encountered. For instance, in the various single-phase locomotives supplied to the Midi Railway, several methods of regenerative braking were tried, but in only one case were satisfactory results obtained.†

The most practicable solution of the problem appears to be obtained by a method somewhat similar to that adopted with continuous-current series motors, viz., to separately excite the field winding and insert a booster in the armature circuit for the purpose of regulating the braking effect.

The current for the separate excitation of the field winding, however, cannot be taken directly from the main transformer, since, in this case, the E.M.F. generated in the armature would have a considerable phase-difference (approximately 90 degrees) with respect to the supply voltage (or the voltage at the secondary terminals of the main transformer). The field winding must, therefore, be excited from a circuit in which the voltage has a phase-difference of 90 degrees with respect to the supply voltage. With no current in the armature, the generated E.M.F. will then be in phase with the supply voltage, and, provided that the equality of the two voltages has been adjusted, the armature may be connected to the supply system. But when the machine is returning current to the supply system, the armature current will not be in phase with the generated E.M.F. Hence, in order that this current shall be in phase with the supply voltage, the phase of the exciting current must be

* See *Electric Railway Journal*, vol. 43, p. 304.

† See paper on "The Electrification Schemes of the Chemins de fer du Midi" by E. J. Jullian. *Journal of the Institution of Electrical Engineers*, vol. 51, p. 566.

changed. Moreover, for satisfactory working, the phase of the exciting current must vary with the variation of the armature current.

When the correct phase relations have been obtained, the regulation of the armature current (or braking effect) is, relatively, a simple matter, and can be carried out by means of an induction regulator or by suitable tapings on the main transformer in conjunction with contactors.

The practical application of this method is found in the electric locomotives supplied by the Jeumont Company to the Midi Railway. The locomotives are equipped with three 500-H.P. compensated series motors, which, for normal running, are all connected in series and controlled by means of induction regulators.*

For regenerative braking, the field (excitation) windings of the motors are separately excited from a special winding on the auxiliary motors driving the compressors and blowers; while the armatures and compen-

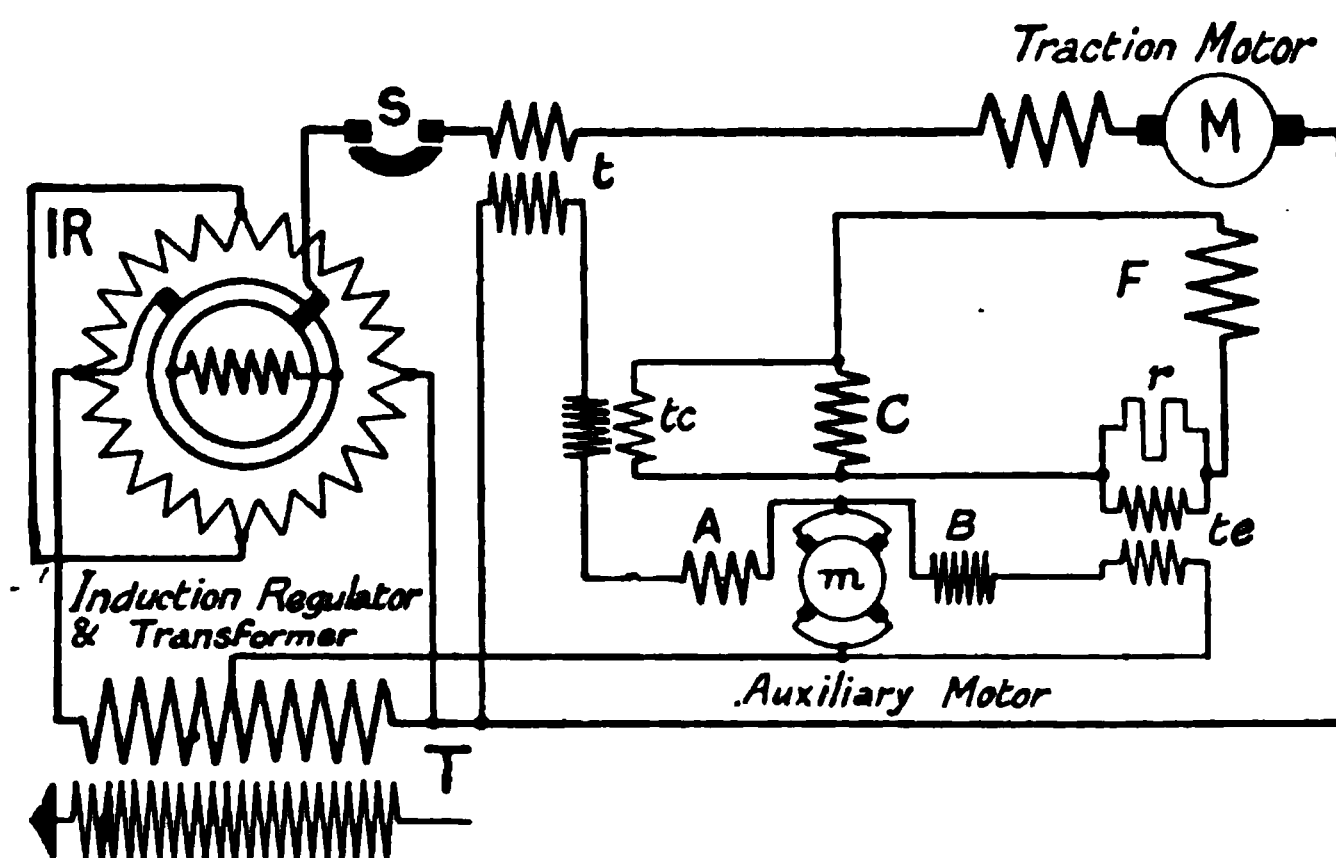


FIG. 226.—Diagram of Connections of Jeumont System of Regenerative Control for Single-phase Railway Motors.

sating windings are arranged in series (as in normal running) and connected to the main transformers through the induction regulators.

A schematic diagram of the connections is shown in Fig. 226. In this diagram only one traction motor (M), one auxiliary motor (m), and one main transformer (T), with induction regulator (IR), are shown. The auxiliary motor (m) is of the Latour compensated-repulsion type, and is provided with a special stator winding C in addition to the main stator winding A , and the shunt winding B , the latter winding being for the purpose of maintaining unity power-factor on the motor. The special winding C is displaced 90 degrees with respect to the main stator winding A , and supplies exciting current to the field winding F of the traction motor.

Hence, at no load the E.M.F. generated in the armature of the traction motor will be in phase-opposition with the supply voltage, and when the equality between the voltages has been adjusted by the induction regulator, the main low-tension switch S may be closed.

* See *The Engineer*, vol. 115, p. 172, for a complete description of these locomotives. A brief description, including a diagram of connections, will be found in *The Electrician*, vol. 70, p. 792.

The phase of the exciting current is varied automatically with the current returned to the supply system by means of the compensating transformer t_c and the series transformer t , while the power-factor of the auxiliary motor is maintained at unity by means of the compounding transformer t_e and the resistance r . The operation of the auxiliary motor is therefore not affected by the current in the winding C .

The above method of regenerative braking has given satisfactory results on the Midi Railway. Tests * with a 280-ton train on a gradient of 1 in 59 (1.7 per cent.) have shown that, at a speed of 23.6 ml.p.h., the power returned to the supply system was 400 kw. (at a power-factor of 0.83), which corresponds to approximately 40 per cent. of the power required by the train in ascending the gradient at the same speed. With a lighter train—weighing 100 tons—the power-factor during recuperation was nearly unity.

With single-phase equipments it is impossible to obtain very high values (such as are common to three-phase equipments) for the ratio of the power recuperated down a gradient to the power required for ascending the gradient under similar conditions, as the overall efficiency of single-phase equipments is considerably lower than that of three-phase equipments. Hence, where recuperation is of importance on a single-phase system, the results obtained with an equipment consisting of three-phase motors and a phase converter will generally be superior to those obtained with a straight single-phase equipment.

* See *The Engineer*, vol. 115, p. 174.

CHAPTER XIII

AUXILIARY ELECTRICAL EQUIPMENT FOR TRAMCARS

IN addition to the motors and controllers, the electrical equipment of a tramcar must include (1) a current collector (in the form of a "trolley" or a "plough"), by means of which the current is conveyed from the overhead line or conductor rails to the controller and motors; (2) rheostats for starting and regulating the speed of the motors; and (3) protective apparatus to protect the equipment against overload and, in the case of overhead systems, against lightning discharges.

The **trolley** collector consists of a standard, a trolley-pole, and a trolley-head. The trolley-head is fixed to the end of the trolley-pole, from which it is insulated, and carries the trolley wheel.

The **trolley-head** may be of the fixed type—which is intended for operating on wires arranged centrally with the track—or of the swivelling type, which is now largely used, and is suitable for operating on trolley wires displaced from the centre of the track. Views illustrating these types of trolley-heads are given in Fig. 227, and the various parts are shown in Fig. 228.

The trolley-wheel is usually made of gun-metal having a high percentage of copper, although, in some cases, a composite wheel—with a copper centre and pressed steel flanges—is used. The diameter at the bottom of the groove is usually 3 in., but for high speeds a larger diameter (about 5 in.) is adopted. The wheel may be fitted with a hollow steel spindle (which is self-lubricating) or with a solid steel spindle and a graphite bush, both types being illustrated in Fig. 228.

In the swivelling type of head, the guard carrying the trolley-wheel is mounted vertically in the trolley-head on a ball bearing or on a ball race. In some types a lubricated "friction washer" is used instead of ball bearings. These details can be observed in Fig. 228.

The **trolley-pole** is a light steel tube, 1 in. in diameter at the trolley-head end, and $1\frac{1}{2}$ or 2 in. in diameter at the butt end. It is about 15 ft. long, and is held in a special fitting on the trolley standard. Rubber sleeves are fitted at each end to insulate the pole from the trolley-head and the standard, while the outside of the pole is covered with two layers of insulating tape.

Two types of **trolley standards** are in use, viz. (1) the vertical type, for use on open double-deck cars, and (2) the dwarf type, for use on single-deck cars and covered double-deck cars.

A section of one type of vertical standard (for double-deck cars without top covers) is shown in Fig. 229. The outer steel tube *B* is fixed

into a cast-iron base *A*, and supports, on ball bearings, the cast-iron head *C*, to which is fixed the internal tube *D*. This tube extends the whole length of the outer tube to a guide bearing *E* in the base *A*. The trolley-pole is fixed to a hooded pole-holder *F*, which is hinged to the

I II III

FIG. 227.—Types of Trolley Heads: I, swivelling head with ball bearing; II, fixed head or "harp"; III, swivelling head with "friction washer."

head of the standard at *G*. A pin *H* is located in the inner portion of the hood, and carries the tension-rod *J*. The upper end of this rod is formed into a square head, while the lower portion is threaded to engage the nut *K*, which is in the form of a cross-bar and is seated in slots in the



FIG. 228.—Parts of the Trolley Heads illustrated in Fig. 227. *A*, body for head III; *B*, body for head II; *C*, body for head I; *D*, trolley wheel with graphite bush; *E*, shield for "friction-washer" type of head; *F*, shield for ball-bearing head; *G*, hollow self-lubricating spindle; *J*, terminal sleeve with cable terminal and insulating bush; *K*, rubber sleeve (for insulating terminal sleeve from trolley pole); *H*, terminal sleeve completely assembled.

casting *L*, the latter being free to move in the tube *D*. A collar *M* is riveted to the inner tube near its upper end, and between this collar and the casting *L* is placed the spring *N*. An adjustable stop *O*, fixed in the head *C*, prevents the trolley-pole from rising above a certain elevation.

It will be seen that the spring is in compression, and that its leverage on the pole-holder is a minimum in the lowest position of the trolley-



FIG. 229.—Section of Trolley Standard for Double-deck Cars without Top Covers (Brecknell, Munro, & Rogers).

head. As the trolley-pole becomes inclined, its effective "arm" decreases: the tension in the rod *J* decreases, and its "arm" increases. Thus, slight deviations of the trolley-pole from the normal operating position will not affect the pressure on the trolley-wire, but under low bridges the pressure will be reduced, thereby avoiding excessive wear on the wire at these places. The variation of pressure is shown in Fig. 229a.

In the standard illustrated in Fig. 229 it is necessary to provide a stop *I*, in order to prevent the trolley-pole being rotated a complete revolution, otherwise the cable would probably be damaged. This objection, however, can be overcome by fitting a **swivelling contact** to the lower end of the inner tube. One type of swivelling contact suitable for the above standard is shown in the detail sketch in Fig. 229. The cable from the trolley-head terminates in a contact *P*, which is fixed to a bush of insulating material *Q*, carried in a cup-shaped

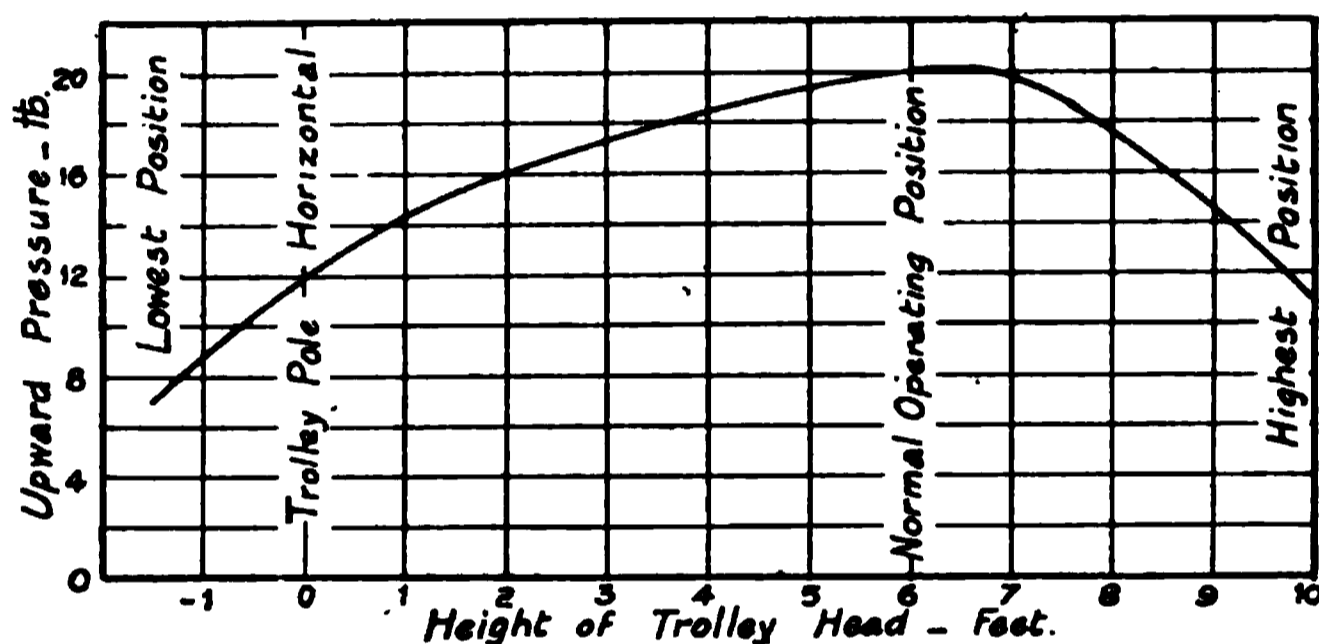


FIG. 229a.—Variation of Pressure on Trolley Wire with Height of Trolley Head. (Distance between centre of trolley head and centre of standard, with trolley-pole horizontal, 14 ft. 6 in.)

casting *R* attached to the lower end of the inner tube *D*. The lower contact *S* works in a guide *T*, which is fixed in an insulating bush *U*, the latter being fixed in a casting *V* bolted to the base of the standard. This contact (*S*) is pressed against the upper contact (*P*) by means of a spring, and a square is formed on the neck of the lower contact to prevent rotation of the cable terminal to which the cable leading to the controller is attached.

The standard must be earthed by a low-resistance fuse or automatic switch (see p. 640) with a bell as the warning signal when the fuse or switch opens. In some cases, however, the standard is earthed through two 200-volt red lamps connected in series.

The extensive use of top covers for double-deck cars has necessitated the development of a trolley standard having a minimum height, in order that these cars may be able to run under low bridges. A trolley standard to fulfil these requirements is shown in Fig. 230. This standard is in extensive use, and can be made so that the total height, when the trolley-pole is horizontal, is only 3½ in. The head of the standard is carried on a central sleeve, forming part of the base, and is provided with ball bearings, while a stop is fitted, as in the above standard, when the base is not furnished with a swivelling contact. The arrangement of the springs, tension-rods, and pole-holder is shown clearly in the illustration.

In conduit tramways the current is conveyed from the conductor rails, in the conduit, to the car by means of a **plough collector**. As the slot is only $\frac{1}{4}$ in. to 1 in. in width, and the full line voltage exists

FIG. 230.—Dwarf Trolley Standard (Brecknell, Munro, & Rogers).

FIG. 231.—Plough Collectors for Conduit Tramways. The plough shown on the right has been developed for cars running on combined conduit and overhead trolley systems.

between the conductor rails—which are only 6 in. apart—it will be apparent that very careful designing is required to obtain a satisfactory collector.

The standard ploughs adopted on the London County Council conduit tramways are shown in Fig. 231. The head *A* is of cast steel, the lower portion *B* is of wood, while the intermediate portion *C* (which passes

through the slot of the conduit) is built up of steel plates. The shoes *D*, which make contact with the conductor rails (see Chapter XXI), are of cast iron, and are pressed outwards by semi-elliptic springs. Each shoe is connected to a terminal, fixed in the base of the plough, by a flexible copper connection *E*, which acts as a fuse in the event of a short-circuit within the plough. The connections

FIG. 232.—Resistance Grid of B.T.-H. Tramcar Rheostat.

between the shoe terminals and the cables *F* (or contacts *G*) at the head of the plough, are in the form of copper strip, in order that they may be carried between the steel plates in the intermediate portion of the plough, the overall thickness of which is only $\frac{1}{4}$ in. The lower portion of the plough is protected from mud, &c., by a hood *H*. The head of the plough is fitted with projections *J*, which slide in the plough carrier (see Fig. 264, p. 312) on the truck.

For cars which have to operate on both conduit and overhead trolley systems, the London County Council Tramways have developed a plough which can easily be removed from the car.* In this plough the head is fitted with spring contact-shoes *G*, instead of cables, and these shoes make contact with two insulated bus-bars fitted to the plough carrier. Before this device was adopted, it was necessary, when changing from the conduit to the trolley system, and *vice versa*, to disconnect and connect the cable connectors under the car. The bus-bars are connected to a change-over switch, from which connections are taken to the controllers and the trolley. In one position of the switch the bus-bars are connected to the controllers and the trolley circuit is isolated, while in the other position the trolley is connected to the controllers and the bus-bars are isolated.

FIG. 233.—B.T.-H. Tramcar Rheostat (for location under car).

Rheostats.—The grid type of rheostat, with mica insulation, is

* For details of the method of removing and replacing the plough, see p. 485.

adopted on all modern equipments. The grids are of a special grade of cast iron, or an alloy of aluminium and cast iron, and are treated with a rust-preventing compound. One form of grid is shown in Fig. 232. In this type each grid is provided with three slotted bosses and a projecting lug, to which a terminal can be fitted. The bosses are ground flat, and the grids are assembled on mica insulated rods, which clamp the whole together. These rods may be mounted in steel end-frames, as in Fig. 233, for location under the car, or in a ventilated cast-iron box, as in Fig. 234, for location on the platform under the staircase. With this type of rheostat, a grid may be readily removed by slackening the nuts on the supporting rods. The series connection of the grids is obtained by inserting a thin mica washer between alternate outside bosses and a similar washer between all the middle bosses.

Protective Devices.—In order to protect the equipment against excessive overload, an automatic overload circuit-breaker is connected between the controller and the current collector. On cars equipped with trolleys this circuit-breaker is mounted under one of the canopies, within reach of the motorman. A switch is connected in series with the circuit-breaker and fixed under the other canopy. With cars operating on the conduit system, where the polarity of the conductor rails is liable to be reversed, it is necessary to provide a double equipment of switches and circuit-breakers, a switch at one end being in series with a circuit-breaker at the other end. The car wiring can therefore be isolated from either end of the car.

The circuit-breakers and switches are provided with a magnetic blow-out for suppressing any arc that may be formed when the circuit is opened. A typical **circuit-breaker** is shown in Fig. 235, the tripping coil—which is also utilised for the magnetic blow-out—being located under the arc chute.

On cars which are operated from an overhead line it is necessary to protect the equipment against lightning. The general practice is to insert a choking coil in the circuit between the circuit-breaker and the controller, with a tap to a lightning arrester on the circuit-breaker side of the choking coil.

There are several **types of lightning arresters** in use, but, as far as the operation is concerned, they may be divided into three classes, viz. (1) the aluminium-cell arrester; (2) the spark-gap arrester, with or without magnetic blow-out; and (3) the non-arcing type of arrester, in which a high resistance is used.

The aluminium-cell arrester, designed for low-voltage continuous-current circuits, has only recently been applied to electric traction. It is more costly and requires more attention than the other types, but it has the advantage of possessing a much greater discharge capacity than other arresters. At the present time it has only been adopted in America, on lines which are subject to frequent lightning storms.*

The spark-gap arrester consists of a short spark-gap in combination with a series resistance, and a means of preventing the line current from following a lightning discharge. The latest development † in this type

* Further details can be obtained from a paper on "Studies of Protection and Protective Apparatus for Electric Railways," by E. E. F. Creighton and others (*Transactions of American Institute of Electrical Engineers*, vol. 31, p. 851).

† *Ibid.*, p. 868. See also *General Electric Review*, vol. 11, p. 927.

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FIG. 234.—B.T.-H. Tramcar Rheostat (for location on car platform).

FIG. 235.—B.T.-H. Automatic Circuit-breaker for Tramcars.

of arrester is the use of the magnetic field of a permanent magnet for suppressing the arc. In the earlier types, an electro-magnet was used, which was excited from a portion of the series resistance. The advantage of the permanent magnet is that a smaller spark-gap can be used, since the magnetic field has not to be built up by the discharge current. With the new type of arrester a spark-gap of .015 in. is adopted, whereas with the older type the gap was .025 in.

The aluminium-cell and magnetic blow-out arresters have been developed principally by the General Electric Co. and the British Thomson-Houston Co.

One form of non-arcing arrester consists of two electrodes and a cylindrical block of specially prepared carborundum of high resistance. The carborundum block has numerous air spaces uniformly distributed throughout its mass. A discharge through the block is, therefore, split up into a large number of smaller discharges, and the high resistance of the material prevents the discharge from being maintained by the line voltage. The carborundum block is separated from the "line" electrode by a small air space. This type of arrester has been standardised by the Westinghouse Co. for traction circuits not exceeding 1000 volts.

The car wiring (see Fig. 236) may be divided into two portions, viz. (1) the wiring for the lights and destination indicators, (2) the wiring for the power circuits. The former is located in casing, with switches and fuses to control the lamp circuits, the supply being tapped off the line side of the canopy switch. Each circuit usually consists of five 105-volt lamps, connected in series.

In modern equipments the wiring for the power circuits consist of two multi-core cables (one along each side of the car), with distinctive colours to the separate cables. These cables interconnect the controllers, and tapplings are brought out at suitable points for connection to the motors, rheostats, and brakes, as shown in Fig. 236.

At Controller No 1, connect cable A₂ to terminal A₂ & cable A₁ to terminal A₁ (See Plan for location of Armature cables A₁, M₁, A₂, M₂)

FIG. 236.—Diagram of Wiring for Power Circuits on Tramcar.

CHAPTER XIV

AUXILIARY ELECTRICAL EQUIPMENT FOR ELECTRIC LOCOMOTIVES AND MOTOR-COACHES

IN addition to the motors and control equipment described in Chapters IV and IX, locomotives and motor-coaches must be equipped with current-collecting gear, apparatus for operating the brakes, apparatus for ventilating the motors (when these are of the forced-ventilated type); while, for high-voltage continuous-current equipments, a motor-generator will be required to supply the lighting and control circuits. With single-phase equipments the control and lighting circuits may be supplied from tappings on the main transformers or from a separate transformer.

Dealing first with the **current-collecting gear**. This is naturally divided into two classes, according to the position of the conductor from which the supply of current is obtained. When conductor rails are adopted, the current collector takes the form of a cast-iron or cast-steel collector-shoe, which is maintained in contact with the conductor rails either by its own weight or by means of a spring.

Collector-shoes may be divided into three types, according to the types of conductor rail (see Chapter XXIII). In this country the top contact conductor rail is generally used, and a typical collector shoe is illustrated in Fig. 237. The contact shoe is supported by a pair of links from two castings bolted to a "shoe plate," the latter being fixed to an insulating support attached to the axle boxes or the motor frame. The links allow of vertical motion of the shoe, and the lowest position of the latter is adjustable by means of the serrations on the shoe-plate and the supporting castings. In most cases the weight of the shoe is of the order of 30 to 40 lb., which is sufficient to ensure satisfactory contact between the shoe and conductor rail. Under normal conditions a shoe of the type illustrated is capable of collecting about 2000 amperes at speeds up to 30 ml.p.h.

When the conductor rails are located outside the track rails, the collector-shoes are attached to an oak beam, which is fixed to the axle-boxes, or to a part of the truck frame directly connected to the axle-boxes, (*e.g.* the equaliser bars in an equalised bogie). In the other position of the conductor rails (*i.e.* between the track rails) the collector-shoe is either attached to an oak block (which is bolted to a bracket fixed to the motor frame) or to an oak beam at the end of the truck, this beam being connected to longitudinal channels carried from the axle-boxes. An example of the application of the first method is shown in

Fig. 277 (p. 332). It should be noted that, when passing round curves, the transverse movements of the shoes will be the greater, the greater the distance of the shoes from the pivotal centre of the truck.

FIG. 237.—B.T.-H. Collector Shoe for Top-contact Conductor Rails.

The under-contact conductor rail (see Fig. 412, p. 497) requires the position of the current-collecting portion of the shoe to be approximately at right angles to the shoe plate. A typical collector-shoe for an

P

D

E

FIG. 238.—B.T.-H. Collector Shoe for Under-contact Conductor Rails.

under-contact conductor rail is illustrated in Fig. 238. The contact portion or slipper *E* is hinged to a bracket *D*, which is bolted to the shoe-plate *P*, and the pressure between the slipper and the conductor rail is obtained by springs. The extreme positions of the slipper are limited

by stops. This type of collector-shoe has also been developed for use with the top-contact type of conductor rail.

The collector shoe which has been developed for the side-contact conductor rail (see Fig. 415) on the 1200-volt lines of the Lancashire

FIG. 239.—Collector Shoe for 1200-volt Side-contact Conductor Rail (Lancashire and Yorkshire Railway). The protective covering over the upper part of the shoe is not in position. In the lower view the shoe is in position against the conductor rail. This view shows also the efficient manner in which the conductor rail is protected.

and Yorkshire Railway is illustrated in Fig. 239. The cast-steel contact-shoe is hinged to a bracket which is bolted to a vertical serrated shoe-plate, the latter being fixed to an oak beam carried on lugs from the axle boxes. The shoe is pressed against the contact surface of the conductor rail by a spiral spring, the normal pressure between the con-

tact surfaces being 25 lb., and the transverse motion being limited by stops. The upper portion of the shoe is completely protected by jarrah wood, the lower edge of the protection being only $4\frac{1}{2}$ in. above the protection on the conductor rail.

The collection of current from an overhead conductor requires a

FIG. 240.—Bow Collector for Single-phase Motor-coaches (London, Brighton, and South Coast Railway).

level trolley wire and a collector of small inertia, so that the latter can readily follow any variations in the height of the trolley wire. The use of the trolley-wheel is generally restricted to tramways, although it is used to some extent on inter-urban railways in America. The current-collecting capacity of the larger wheels may be as high as 800 amperes at low speeds, and 200 amperes at speeds of from 50 to 60 ml.p.h.* On a large railway system, however, the use of a trolley wheel would not be

* This current-collecting capacity can only be obtained with a level trolley wire.

tolerated, and the current collector must be of the bow or pantagraph type.

The **bow collector** (Fig. 240) is largely used on the Continent, and is an adaptation of the collector used on Continental tramways, while the **pantagraph collector** (Fig. 241) is standard for all the important electrifications in America.

The collector, whether of the bow or pantagraph type, is usually

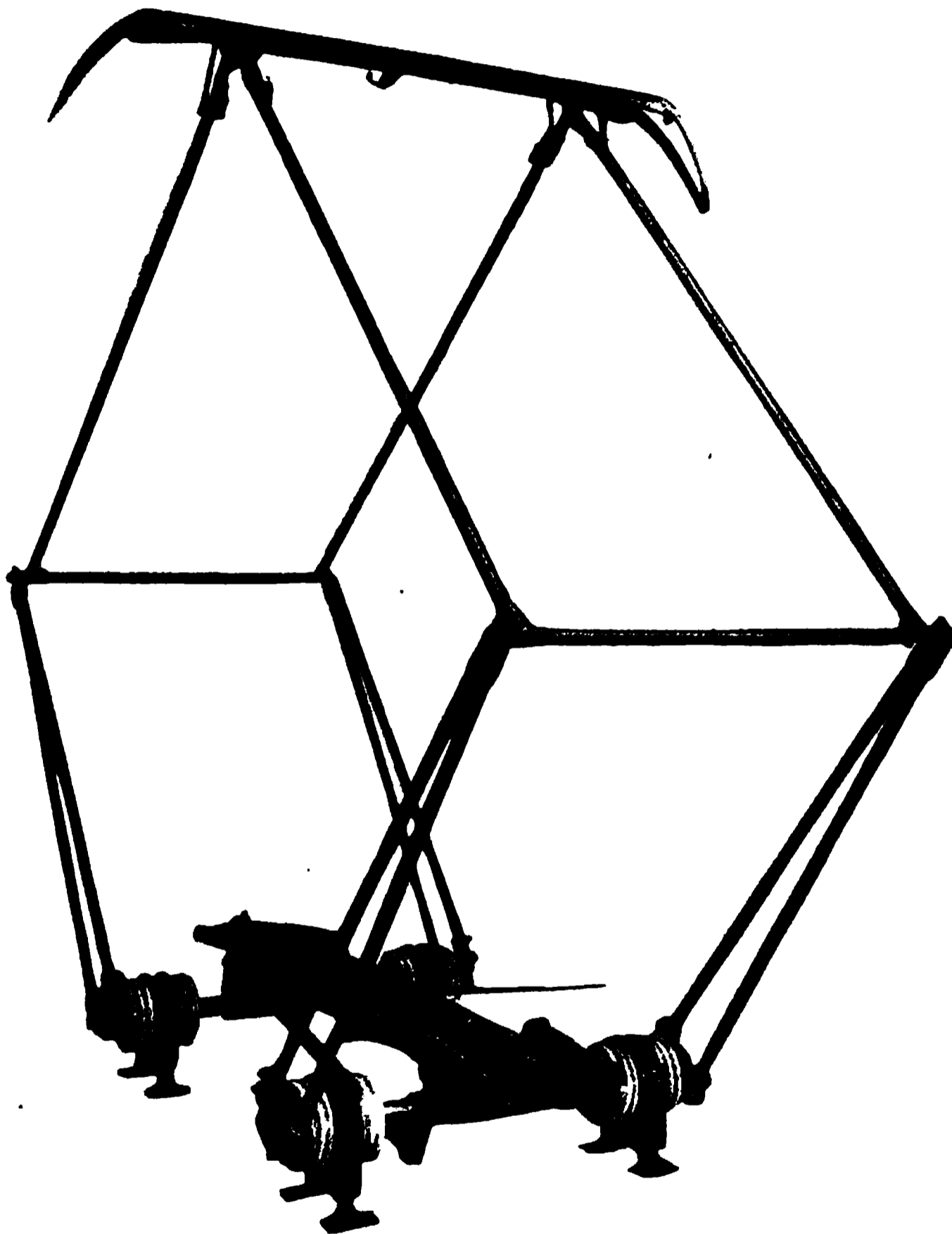


FIG. 241.—Westinghouse Pantagraph Collector for Single-phase Locomotives and Motor-coaches.

maintained in contact with the trolley wire by means of springs, while the raising and lowering operations are performed by air cylinders as described below.

A typical **example of a bow collector** is illustrated in Fig. 240. Collectors of this type are in service on the motor-coach trains running on the suburban (6600-volt single-phase) lines of the London, Brighton, and South Coast Railway, and operate over a wide range of positions,

the lowest position of the trolley wire being about 14 ft. above the rails, while the highest position is 21 ft. Two bows (one for each direction of motion) are arranged on a channel-steel framework, which is mounted on a double set of insulators located on a flat portion of the roof over the luggage compartment of the coach. The bows, when lowered, are arranged to lie inside each other, so that the overall height of the current-collecting apparatus is reduced to a minimum. Each bow consists of a light tubular framework which is fixed to a shaft, the latter being mounted

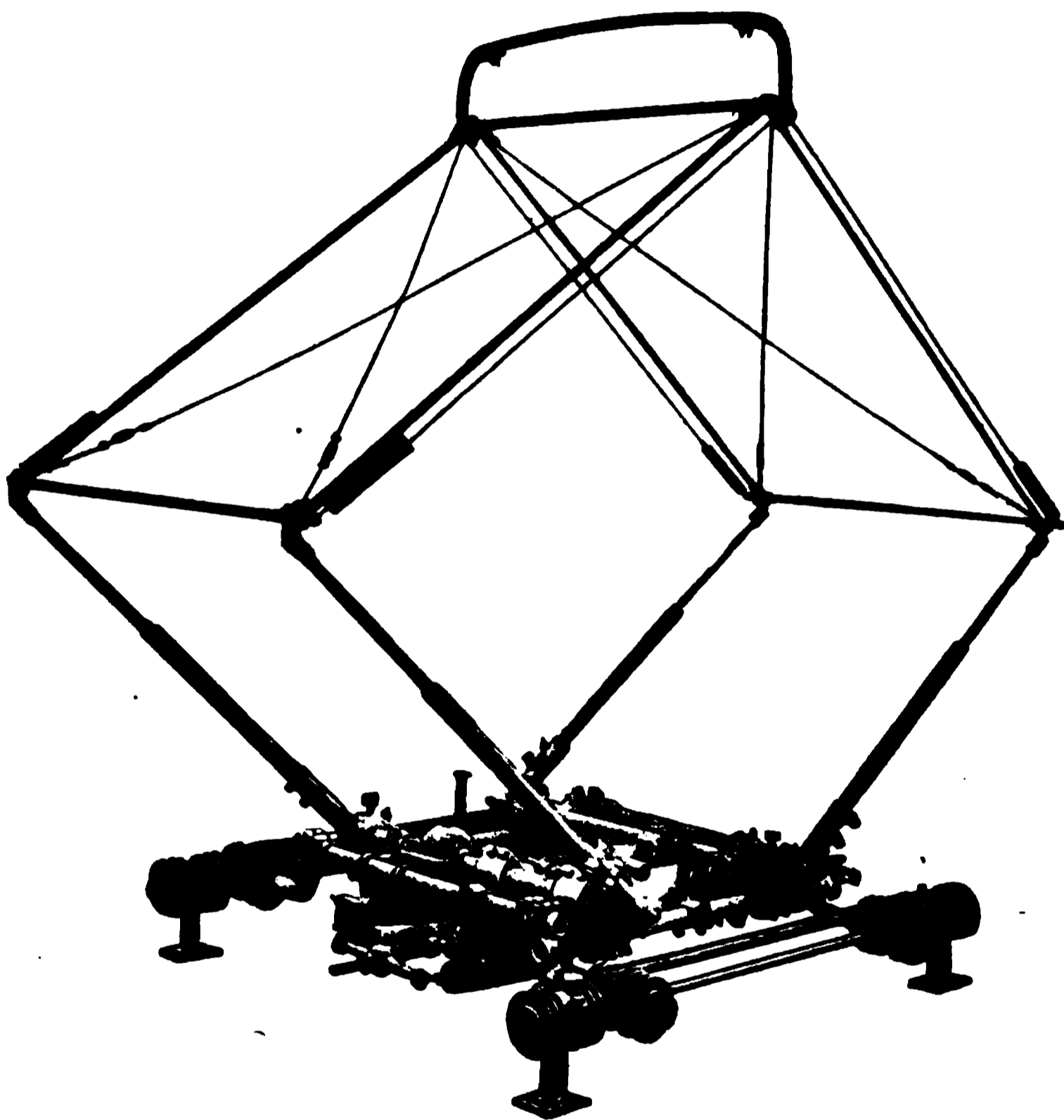


FIG. 242.—Oerlikon Pantagraph Collector for Single-phase Locomotives.

in bearings carried on a channel-steel framework. The bow is maintained in the raised position by means of an air cylinder acting against a set of springs, the piston-rod and springs being connected to levers on the shaft (the piston-rod, of course, being insulated from the shaft). The springs and levers are arranged to give a uniform pressure (of about 12 lb.) between the bow and the trolley wire over the whole operating range.

The air cylinders are supplied with compressed air * from a distributing valve, which is operated by the reverser, so that the bow in

* A hand pump is provided for raising the bow when there is no air supply.

contact with the trolley wire corresponds to the position of the reverser. Thus, when the train is reversed, the bows change over automatically as soon as the reverser is thrown to the "reverse" position. In changing over, the second bow is raised before the one in contact with the trolley wire is lowered: this avoids interrupting the primary circuit of the main transformers.

The top portion of each bow, which makes contact with the trolley wire, is fitted with a wearing-strip of aluminium, and this wearing-strip is provided with a groove for the reception of a lubricant (generally a mixture of vaseline and graphite). The wearing-strips will run about 6000 miles before requiring renewal.

The current is conveyed to the high-tension chamber (which is

FIG. 243.—Roller Pantagraph Collector (lowered) for 2400-volt Continuous-current Locomotive (Butte, Anaconda, and Pacific Railway).

located in the end of the coach under the bows) by a connection which passes through a special insulator in the roof. Each bow is mechanically interlocked with the doors of the high-tension chamber so that this chamber cannot be opened until both bows are lowered.* (See Chapter XVI, p. 348, for particulars of the high-tension chamber.)

When a single bow collector is required to operate in both directions of motion, the upper portion of the bow framework is fitted with a small reversing bow, which is spring controlled independently of the main framework; the latter, of course, being controlled by springs and air pressure in the usual manner. This auxiliary bow forms the current collector and accommodates itself to slight variations in the height of the trolley wire, large variations in height being taken care of by the main framework. Examples of bow collectors operating on this principle will be found in Figs. 341, 342 (p. 404). In these cases (which refer to three-phase railways) the main framework of each collector is

* All high-tension chambers should be fitted with a device of this nature, and as an additional precaution, the opening of the doors should automatically earth the connection from the bows.

fitted with two auxiliary bows, which are insulated from the framework, since the wires with which they make contact belong to different phases of the supply system.

The **pantagraph collector** (Fig. 241) consists of a light pentagonal framework with the lower members fixed to shafts which work in bearings formed in the supporting insulators. The apex of the framework carries the current collector, which may be in the form of a sliding contact-strip or a roller. The shafts are inter-connected by linkwork so that the apex of the collector is constrained to move in a straight line perpendicular to the base. Each shaft is also fitted with levers, to which the controlling springs and piston-rods of the air cylinders are connected.

FIG. 244.—B.T.-H. Motor-driven Air Compressor; Geared Type for Motor-coaches.

Usually the collector is maintained in the raised position by the springs (which are in tension), and it is lowered by admitting air to the cylinder. With this method of operation the collector must be locked in its lowest position in order to prevent it rising due to leakage of air from the cylinder. The collector is raised by admitting air to an auxiliary cylinder (thereby releasing the locking-down catch) and releasing the air from the main cylinder.

When the current-collector is of the sliding-contact type, the contact may consist of a strip of aluminium fixed to a small bow pivoted to the top of the pantagraph, as shown in Fig. 242. This type of collector is in use on the Continent, but in this country and America the sliding contact is of the "pan" type, and consists of a thin sheet of steel—about 6 in. wide—provided with a groove for the reception of the lubricant. The pan is pivoted to the top of the pantagraph frame and is fitted with supplementary springs to ensure an even contact. In some recent types of this collector two pans are provided, each about 5 in. wide by 42 in. long, the upper surfaces of which are fitted

with copper bars which results in a large current-collecting capacity.* With the ordinary type of sheet steel pan the current-collecting capacity is limited to about 150 amperes at moderate speeds, which is also the limit for the bow type of collector.

A larger current-collecting capacity can be obtained from a rolling contact, since a greater pressure can be used between the roller and the trolley wire than is possible with a sliding contact. A **roller pantagraph collector** is illustrated in Fig. 243. The roller (which usually consists of a steel tube 5 in. in external diameter, $\frac{1}{2}$ in. thick and 2 ft. long) is carried in ball (or roller bearings) at the top of the pantagraph frame,



FIG. 245.—Oerlikon Motor-driven Air Compressor for Single-phase Locomotives (direct drive).

and the latter is provided with downwardly projecting horns to prevent the collector fouling the wires at junctions.†

A single roller is capable of collecting a current of 500 amperes at moderate speeds, and has a life considerably longer than that of the sliding type of collectors. ‡

The auxiliary apparatus required for operating the brakes§

* A collector of this type has successfully collected 2000 amperes at speeds up to 40 m.p.h. See *General Electric Review*, vol. 17, p. 1131.

† For further data relating to roller-type pantagraph collectors, see papers in the June and August (1915) numbers (vol. 34) of the *Proceedings of the American Institute of Electrical Engineers*.

‡ The life of the contact portion of the roller has been stated to be over 15,000 miles in a service requiring the collection of 500 amperes during acceleration. See *General Electric Review*, vol. 17, p. 1130.

§ A description of the equipment for the compressed air and vacuum brakes is given at the end of Chapter XVI.

comprises an electrically-driven compressor (or exhauster) and means for automatically maintaining the air pressure (or vacuum) at the correct value.

The compressor is usually of the single-stage two-cylinder, single-acting type, and is driven by a small motor (of 5 to 10 H.P.), the motor and compressor being bolted together to form a self-contained unit (see Figs. 244, 245). With compressors for motor-coaches, a moderate-speed motor is adopted in order to reduce the weight, and the compressor is driven through double-helical spur gearing. Fig. 244 is representative of compressors for motor-coaches. With compressor equipments for locomotives, a slow-speed motor can be adopted, and the compressor is then driven directly from the armature shaft, as shown in Fig. 245.

The motor is of the series type for continuous-current circuits, but, for alternating-current circuits, either the series or the repulsion types are available. The starting and stopping of the motor is controlled by a contactor (called the governor) actuated by air pressure.

The single-stage compressors for use on motor-coaches and light locomotives are built in various capacities

FIG. 246.—B.T.H. (Type ML) Governor for Controlling Air-compressor Motor.

up to 50 cubic ft. (piston displacement) per minute at normal air pressure (80 to 90 lb. per sq. in.). When larger compressors are required (e.g. for heavy locomotives hauling long trains equipped with air brakes) the two-stage type, with three or four cylinders, is adopted. In this case higher pressures (up to 160 lb. per sq. in.) are used, and an inter-cooler is provided between the low- and high-pressure cylinders.

A governor is illustrated in Fig. 246. The operating mechanism consists of a piston *A*, which is pressed against a diaphragm *B* by a strong spring *C*, the other side, *D*, of the diaphragm being connected to the main reservoir. The piston operates the contactor *E* through a linkwork which is designed to give a quick closing and a quick opening action to the contacts. The governor is designed so that the contactor will open at a given air pressure and close when a slight reduction in pressure takes place, the difference between the opening and closing pressures being adjustable between 8 to 15 lb. per sq. in. The air pressure at which the contactor opens depends on the compressive force of the spring, and the latter can be adjusted, within certain limits,* by means of suit-

* The standard limits are :—40-60 ; 65-100 ; 100-140 lb. per sq. in.

able screws in the closed end of the cylinder. The contactor is provided with a magnetic blow-out and connects the motor directly to the circuit, the motor being designed so that the initial current-rush on a 600-volt circuit does not exceed about twice the normal running current.

The **exhauster or vacuum pump** (which is used with vacuum brakes) is usually driven from the motor through a spring coupling. In some cases the motor is run continuously at half-speed (for the purpose of maintaining the vacuum), and is automatically switched over to full speed when the brake valve is moved to the "off" or "release" position. In other cases the motor is controlled by an automatic governor

which is arranged to start the motor when the vacuum falls to 15 in.

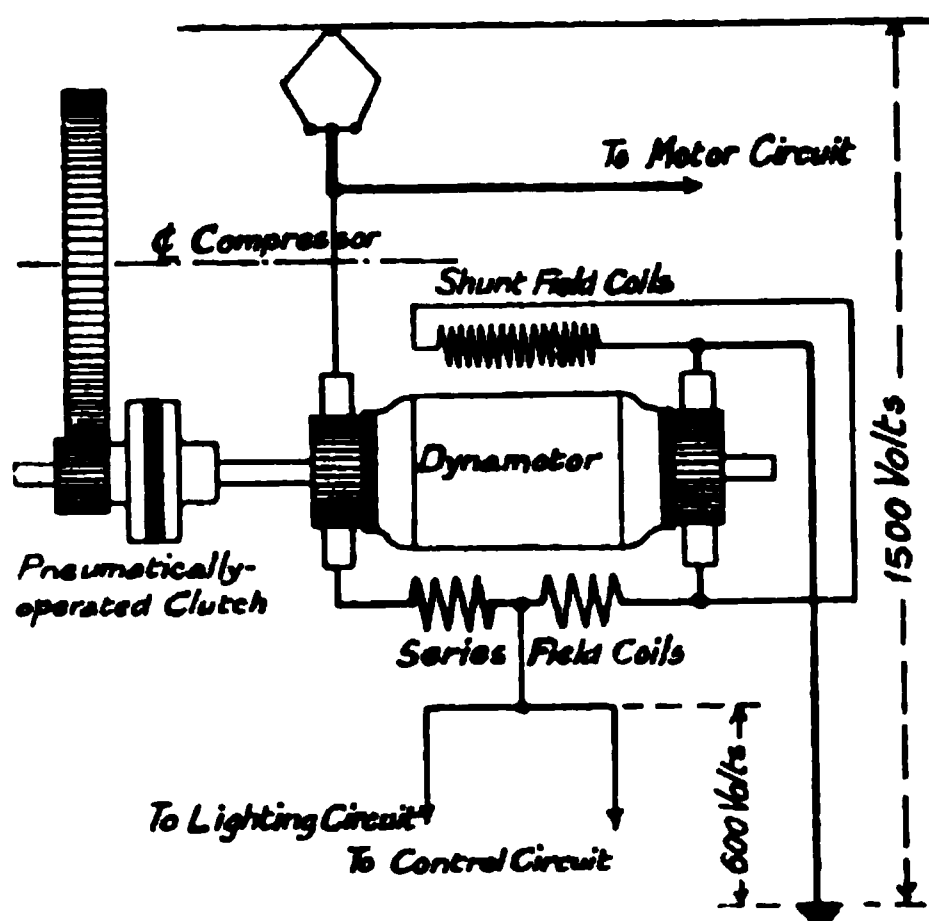


FIG. 247.—Diagram of Circuits of Dynamotor.

An **electrically - driven blower** is required on locomotives when forced-ventilated motors are used. The blower delivers air at a small pressure (6 to 8 in. of water) into a central duct—built into the underframe of the locomotive body—from which it is distributed to the motors. Blowers are sometimes adopted on single-phase motor-coaches, as for example on the Midland Railway.

Dynamotor.—When continuous-current railways operate at voltages above 750 volts, it is necessary to provide a machine to supply the lighting and control circuits with current at a suitable voltage (*e.g.* 500 to 600 volts). For this purpose a continuous-current motor-generator—consisting of a high-voltage motor and a low-voltage generator—could be used, but a more efficient and less costly machine can be obtained by the use of a common field frame and armature core, the latter being wound with two windings, each of which is connected to a separate commutator. Such a machine is known as a "dynamotor" or reducer.

When the ratio of the voltages is small, the two armature windings may be connected in series across the supply, as shown in Fig. 247. This arrangement of the connections resembles that of the alternating-current auto-transformer, and results in a light and an efficient machine. Thus, if the machine is for use on a 1200-volt circuit, each armature winding would be wound with the same number of turns, of practically the same size of conductor, while the commutators would have the same number of segments, although the commutator on the "line" side would require to be insulated for 1200 volts to earth. A machine of this kind is generally provided with two series windings and a shunt winding—connected as shown in Fig. 247—the connection to the lighting and control circuits being taken from the junction of the two series windings. When there is no load on the low-voltage circuit, both

armatures are connected in series, and all the field windings are acting in the same direction, the excitation being derived almost entirely from the shunt winding. When the low-voltage circuit is loaded, the armature connected to the line acts as a motor, while the other armature acts as a generator, so that its series field is in the opposite direction to that of the motor and the shunt winding. By suitably proportioning the two series windings, a practically constant flux and speed can be obtained for all loads.

In America the dynamotor has been combined with the compressor and the blower, the latter being mounted on an extension of the armature shaft, while the former is driven through a pneumatically-operated clutch controlled by the air pressure in the main reservoir. In this manner a considerable saving in weight and space is obtained. Of course, with a machine of this type the speed will not remain constant at all loads, but will be lower when the compressor is working, due to the additional series field ampere-turns produced by the motor.

CHAPTER XV

ROLLING STOCK FOR ELECTRIC TRAMWAYS

THE double-deck type of car, mounted on either a single truck or a pair of bogie trucks, is used almost exclusively on tramways in this country, and on the larger systems the upper deck is usually covered in. In some cases the top-deck covers are removable, but more generally they are integral with the car-body, and the sides are provided with drop sashes.

The single-deck type of car has only a limited application in this country, and is adopted where the conditions are not favourable for double-deck cars. In America and on the Continent, however, the climatic conditions necessitate a closed car, and the double-deck car is the exception. Moreover, in some American cities there is insufficient headroom for the ordinary double-deck car, and the recent introduction of this type of car in New York required a special design, having a total height of 13 ft. 6 in. (against 16 ft. for a standard British design). The type of car is, of course, largely influenced by the traffic conditions, which in America require a car which can be loaded and unloaded in the minimum time.

Among the **considerations which affect the choice of a car** for a given line, the following are the more important: (1) gauge, curvature, and contour of the track; (2) height of the lowest bridge from the track; (3) class of traffic.

The **gauge** influences the total width of the car-body, and consequently the passenger accommodation. With the usual arrangement of longitudinal side-seats on the lower deck, the width of the car will affect the gangway, but not the seating accommodation. On the upper deck, however, where the seats are arranged transversely, the seating capacity will be considerably restricted on narrow-gauge lines. Thus, with standard (4 ft. 8½ in.) gauge, four passengers can be comfortably accommodated in each row, but with the 3 ft. gauge it is only possible to accommodate two passengers in each row (unless the gangway is made very narrow). The width of the car is governed, to some extent, by the width of the street, as it is necessary to provide a minimum clearance of 15 in. between passing cars, and between cars and any standing work. With standard gauge the maximum width of car allowed is about 7 ft.

The **curvature of the track** affects the wheel-base, which, with single-truck cars, affects the length of the car. A curve of 30 ft. radius can be negotiated by a single-truck car with a rigid wheel-base of 6 ft., but to avoid excessive track wear the wheel-base should not exceed

5 ft. 6 in. Thus, when this type of truck is adopted, the length of the car is restricted. If the nature of the traffic warrants a larger car, then it will be necessary to adopt either double (or bogie) trucks or a radial truck.

The **contour of the line** affects not only the car but also the electrical and braking equipment. Light single-truck cars are alone permissible on heavy gradients.

The **height of the lowest bridge** on the system affects the head room on each deck, and if the conditions are such that a standard double-deck car cannot be used, then either a special car must be designed or the single-deck car adopted.

The **class of traffic** is usually the deciding feature in the length of the car. Heavy traffic, of course, requires large cars mounted on bogie trucks, but if heavy gradients have to be negotiated it may be necessary to adopt single-truck cars.

CARS

A typical example of a modern double-deck car mounted on a single truck (of the Peckham swing-axle type) is shown in Fig. 248. The car is provided with a covered top deck and vestibuled platforms on the lower deck.* On some cars the vestibule can be completely closed with doors, as shown in Fig. 248a.

As the standard type of car is sufficiently well known to render a detailed description unnecessary, we shall now consider some new types of cars which have been designed to facilitate the expeditious handling of heavy traffic. Of these the **Liverpool twin-staircase car** †—illustrated in Fig. 249—is perhaps the most interesting example in this country. It will be seen that two staircases are provided at each end of the car—one for the passengers entering and the other for the passengers leaving—while the platforms are unusually large, in order to facilitate the transference of the passengers to the upper and lower decks. The car has a seating capacity for 72 passengers (32 on lower deck, 40 on upper deck), while standing-room is provided for 9 passengers on the lower deck. The car illustrated in Fig. 249 is mounted on a Peckham radial-axle truck, but a number of similar cars are mounted on rigid-axle trucks (of the type shown in Fig. 253, p. 301) with a wheel-base of 8 ft. The equipment of these cars consists of two 50-H.P. commutating-pole motors. The principal dimensions and weight of the car are given in Table X, together with those of standard cars.

In America the cars recently introduced for heavy street traffic are of the **centre-entrance** (or “stepless”) type, with the pay-as-you-enter (P-A-Y-E) ‡ system of fare collection, and as an example we may consider briefly the cars operating on the New York conduit lines. A view of a single-deck car is shown in Fig. 250.

The car-body is built of steel, with the exception of the floor, window-posts, head-lining, and roof-boards. The floor at the entrance is only

* These vestibuled platforms have recently been introduced on a number of tramways in this country.

† Designed by Mr. C. W. Mallins (General Manager, Liverpool Corporation Tramways), to whom the author is indebted for the photograph of this car and the data given in the text and Table X.

‡ This system of fare collection is largely adopted in America for city traffic.

10 in. above the track rails, and at the motorman's compartments it is raised to 2 ft. 8 $\frac{1}{2}$ in. so as to clear the motors. At the ends of the passenger compartment, however, the floor is 16 in. above the rails. The low floor has necessitated the use of trucks with exceptionally low bolsters, the top of the bolster being only 12 $\frac{1}{4}$ in. above the rails.

The centre-entrance principle has also been incorporated into the design of double-deck cars, of which an example is illustrated in Fig. 251.

FIG. 248.—Modern British Double-deck Car with Covered Upper Deck and Vestibule
(Built by the Brush Electrical Engineering Co.).

This type of car is also in service in New York, and has been designed with a very low overall height, in order to clear the viaducts of the elevated railways. The car accommodates an exceptionally large number of standing passengers—42 on the lower deck and 41 on the upper deck although the seating capacity (88) is only slightly greater than that (78) of the double-deck cars on the London County Council tramways. The seating and standing capacity of each of these centre-

entrance cars, together with the weights and principal dimensions, are given in Table X.*

With the centre-entrance type of car it is essential that the underframe, and a large portion of the car-body, be constructed of steel in order to obtain sufficient strength. A steel construction usually results in an increased weight, so that it is necessary to design all parts carefully with the object of avoiding the use of any unnecessary material.

FIG. 248a.—Vestibule of Double-deck Car—Salford Tramways
(Brush Electrical Engineering Co.).

Fig. 252 illustrates a **steel car-body** (for a centre-entrance car) during construction.

With the standard type of double-deck car, the car-body is built principally of wood, while the underframe is constructed either of oak (with the principal members reinforced by steel sections or steel plates), or entirely of rolled steel sections.

The underframe for a bogie car is usually constructed entirely of steel sections, as, in this case, the entire weight of the car must be supported at two points, viz. the truck bolsters.

The floor is usually constructed of pine boards, provided with slats of hard wood for wearing purposes, and two or more removable traps are fitted over the motors to allow of the latter being inspected.

* Further particulars of these cars will be found in the *Electric Railway Journal*, vols. 39, p. 418; 40, p. 210. See also *The Electrician*, vol. 69, pp. 448 and 896.

FIG. 249.—Liverpool Train-staircase Car.

The roof of cars which are equipped with trolleys must be specially reinforced to withstand the strains produced by the trolley. It is the usual practice to fix the trolley to a "trolley board," extending nearly

FIG. 250.—Centre-entrance, Single-deck, "Stepless" Car, built by the J. G. Brill Co. for the New York Conduit Tramways.

FIG. 251.—Centre-entrance, Double-deck, "Stepless" Car, built by the J. G. Brill Co. for the New York Conduit Tramways.

FIG. 252.—Steel Car-body for Centre-entrance, Single-deck Car in course of construction (J. G. Brill Co.)

the whole length of the roof, and to construct the latter with alternate car-lines of steel.

A reference to the Board of Trade regulations (p. 640) will show that it is necessary to provide cars with folding steps, collapsible gates, life guards, head and rear lights, destination indicators, gongs, mechanical brakes, and sanding gear. A number of these fittings can be seen in Figs. 248, 248a.

TABLE X
DATA OF TRAMCARS

Class of Car.	Standard British Double- deck, Single- truck Car.	Standard London County Council Cars.		Liverpool Twin- staircase Car, Single Truck.	New York Centre- entrance Cars.	
		Double Deck, Bogie Trucks.	Single Deck, Bogie Trucks.		Single Deck, Bogie Trucks.	Double Deck, Bogie Trucks.
Length over all	30' 0"	33' 10"	33' 9"	33' 4"	40' 8"	44' 0"
Length of body (over corner posts)	16' 4"	22' 2"	24' 10"	17' 4"	34' 0"	34' 4½"
Length of each platform	6' 0"	5' 10"	3' 8½"	7' 6"	3' 10"	8' 10"
Width over all (maximum)	7' 0½"	7' 1"	6' 10"	7' 4"	centre entrance 8' 3"	centre entrance 8' 5"
Width over side pillars of body	6' 9"	6' 8"	6' 8"	6' 10½"	8' 2"	8' 2"
Width over side sills (at floor level)	6' 0"	6' 8"	6' 8"	6' 6"	8' 2"	8' 2"
Clear height of lower saloon at centre	6' 4"	6' 2½"	8' 1½"	6' 5"	7' 11½"	6' 9"
Clear height of upper saloon at centre	5' 10½"	6' 1½"	..	6' 2"	..	6' 1½"
Height of floor above rail	2' 10"	2' 9½"	2' 9½"	2' 10½"	10" at centre entrance	(at gangway). 11" at centre entrance
Total height to top of trolley-board (from rails)	15' 8"	15' 8½"	..	16' 2"	..	12' 10"
Total height over dwarf trolley standard (from rails)	16' 1"	16' 1½"	..	16' 8"	..	..
Number of seated pas- sengers (lower deck)	22	32	36	32	51	44
Number of seated pas- sengers (upper deck)	36	46	..	40	..	44
Number of standing pas- sengers (lower deck)	0	11	12	9	38	42
Number of standing pas- sengers (upper deck)	0	0	..	0	..	41
Maximum number of passengers	58	89	48	81	89	171
Class of truck	21E	maximum traction	maximum traction	21E	maximum traction	maximum traction
Wheel-base	6' 6"	4' 6"	4' 6"	8' 0"	5' 0"	5' 0"
Diameter of wheels	32½"	{ 31½" 21½"	{ 31½" 21½"	32½"	{ 30" 19"	{ 30" 19"
Centres of bolsters . . . . .	..	10' 6"	10' 6"	..	20' 0"	20' 0"
Motor equipment	2-40 H.P.	2-42 H.P.	2-42 H.P.	2-50 H.P.	2-50 H.P.	2-60 H.P.
Weight of car fully equip- ped but without pas- sengers	10½ tons	14½ tons	14.4 tons	13½ tons	16½ tons	20½ tons
Weight of car with maxi- mum number of pas- sengers	14½ tons	20.4 tons	17.4 tons	18.7 tons	21.8 tons.	31.3 tons

* Clerestory roof.

TRUCKS

Trucks for tramcars may be divided into two classes, viz. (1) single trucks, (2) bogie trucks.

Single trucks may be subdivided into three types, viz. (a) trucks in which the axles are maintained rigidly parallel (called rigid-axle trucks), (b) trucks in which the axles are allowed transverse oscillatory movement (called swing-axle trucks), (c) trucks in which the axles are allowed radial as well as transverse movement (called radial-axle trucks).

Bogie trucks may be subdivided into two types, viz. (d) the maximum traction bogie truck, in which the pivotal centre is displaced from the centre of the truck towards one of the axles, (e) the equal-wheel bogie truck, in which the pivotal centre coincides with the centre of the truck. Each of these types may be fitted with either rigid axles or swing axles.

The choice of the truck is influenced by the length of the car and the curvature of the track. Thus a car 18 ft. over the body can be accommodated on a single truck with rigid or swing axles, provided that the curvature of the track will allow of the use of an 8-ft. wheel-base. With the usual wheel-base of 6 ft., the length of the car is limited to 16 ft. over the body and 27 ft. over the platforms. Longer cars, up to 23 ft. over the body and 33 ft. overall, can be accommodated on single trucks with radial axles, where a wheel-base up to 13 ft. can be adopted. Where cars exceed this length it is necessary to use bogie trucks, the wheel-base of which, for tramway purposes, is usually from 4 ft. to 4 ft. 6 in.

The essential parts of a rigid-axle single truck are: (1) the truck frame, which contains the guides for the axle-boxes; (2) the wheels,

FIG. 253.—Brill "21 E" Rigid-axle. Single Truck.

axles, and the axle-boxes; (3) the supports for the car body; (4) the spring system; and (5) the motor suspension. The relative positions of these parts are shown in Figs. 253, 254, which illustrate a truck in very extensive use.*

This truck consists of two forged steel side-frames *A* held together by the end frames *B* and the diagonal brace *C*. In each side frame two yokes are formed, which are machined to receive the journal- or axle-boxes *D*. The latter are provided with double "wings" or pockets for the reception of the springs *E* which support the side-frames and everything connected thereto.

The spring posts *F*, of which there are four to each side frame, are connected together at the top by the "top plates" *G*—to which the side-sills (or sole-bars) of the car-body are fixed—and at the bottom by the truss-rods *H*. The posts pass through holes in the side frames, thereby maintaining the car-body and the truck in the correct positions, and taking all the thrusts between these members.

The car-body is supported on the side frames by a compound spring system, consisting of eight spiral springs *J* and four semi-elliptic springs *K*, the function of the latter springs being to damp the oscillations of the car-body when the car is running at moderate speeds.

* Originally developed by the J. G. Brill Co., and known as the "21 E" truck. It is also manufactured by several firms in this country. The truck shown in Fig. 253 is fitted with the latest type (known as "wide wing") axle-boxes, which give the truck a longer spring base than the original type of axle-boxes (in which the springs were located nearer to the yoke), thereby improving the riding qualities.

Arrang
and
Gaw

FIG. 254.—Outline Drawings of "21 E" Truck. NOTE.—The extended truss rods are only used with long cars.

It will be seen, therefore, that the car-body has a limited vertical motion, relative to the truck, while any side motion is resisted by the semi-elliptic springs, since the spring posts are allowed some "side play" in the frames.

The motor suspension-bars *L* are supported on the side frames by a double set of springs, and in this manner the unsprung-borne load on the axle is only about 50 per cent. of the weight of the motor.

The **axle-boxes** are of malleable iron (or cast steel) and contain a bearing liner, which rests on the upper part of the axle journal. The lower portion of the box forms an oil well, and the journal is lubricated on the pad system. Illustrations of typical axle-boxes are given in Figs. 255*a* and 255*b*. In the axle-box shown in Fig. 255*a*, the end play of the axle is limited by a check-plate which bears in a groove formed in the end of the axle; while in Fig. 255*b* the end play is limited by shoulders at each end of the journal, the outer shoulders being obtained by forming the ends of the axle into "button heads."

The **brake system** provides for a separate brake block to each wheel, the

FIG. 255*a*.—Brill Axle-box (Tramway Type). *A*, cover; *B*, check-plate; *C*, bearing; *D*, oiler; *E*, fibre washer; *F*, collar.

brake blocks being suspended from a pair of links carried from brackets fixed to the end frames of the truck (see Fig. 254). A recent development is the provision of *spherical seats*, where the links are hinged to the brackets and brake shoes, thereby forming an automatic adjustment for wear. The brake shoes for each pair of wheels are fixed to transverse bars *M* (Fig. 254), called the "brake-beams," each of which carries a fulcrum for the brake-levers *N*, to which the pull-rods from the operating spindles on the platforms are attached.

The pressure between the brake shoes is equalised by means of the transverse bars *O* (called "equalising levers"), which are connected together by the adjustable rods *R*. At the centre of each equalising lever is fixed a bracket *P*, which is connected to the brake-lever by a pin *Q*. The brake shoes are released by the combined action of gravity and springs, the latter being attached to the brake-beams and to some fixed part of the truck, *e.g.* the wheel guards when spiral springs are used, and the end frames when flat springs are used.*

When an application of the brakes is made from, say, the forward end of the car, the front brake lever (*N*) turns about the fulcrum *T*, thereby moving apart the front brake-beam and equalising lever. If

* See Fig. 261 for a detail view of the brake gear. Although this illustration refers to a radial-axle truck, the general arrangement of the brake beams, equalising levers, brake levers, and pull-off springs is identical with that on a rigid-axle truck.

the rods *R* are properly adjusted, the front and the rear brake shoes will be moved towards the wheels, the rear brake-beam being moved forward by means of the rear equalising lever. As soon as the front pair of brake shoes touch the wheels, the front brake-beam is fixed, and the thrust is transmitted to the rear brake-beam through the rods *R* and the equalising levers. Thus the whole of the brakes are operated from one pull-rod. The brake-levers are duplicated in order that the brakes may be applied from either end of the car.

FIG. 255b.—Brill Axle-box (M.C.B. Railway Type).

The following particulars refer to this truck :—

Gauge	4 ft. 8½ in.
Wheel base (E, Fig. 253)	6 „ 0 „
Spring base of car-body springs (G)	14 „ 6 „
Length over top plates (F)	15 „ 7 „
Width over top plates (A)	6 „ 0 „
Centres of top plates and side frames (B)	5 „ 9¼ „
Width overall (D)	7 „ 0 „
Diameter of wheels	30 „
Diameter of axles	4 „
Diameter of journals	3½ „
Height from track rail to top plates with empty car body in position	2 „ 1½ „
Weight without wheels and axles	3000 lb.

The **swing-axle truck** has been developed by the Peckham Truck Co. and the J. G. Brill Co. This type of truck is in service on a number of tramways in this country.

A view of the Peckham truck is shown in Fig. 256.* It will be observed that the side-frames and spring system of the truck are similar to those of the 21 E truck described above.

* The truck is built by the Brush Electrical Engineering Co., who are also the manufacturers of the Peckham Radial Trucks described later.

FIG. 256.—Peckham "P 22" Swing-axle Truck.

FIG. 258.—Brill "21 E, s.L." Swing-axle Truck.

The swing or pendulum gear is shown in detail in Fig. 257. An examination of this drawing will show that the axle-box springs are carried on a short supporting frame *A*, which is hinged to a saddle *B*, the latter being pivoted to the top of the axle-boxes. The saddle is provided with flanges which extend outside the side frame and limit the swing. It will be apparent that with this device the axles can move laterally *independently of the truck frame and car-body*, so that the axles can adapt themselves to irregularities in the track without transmitting the effects to the car-body.

Trucks of this type are, therefore, characterised by easier riding and freedom from side oscillations. Moreover, the blows delivered to the rail head by the flanges of the wheels are considerably smaller than with trucks of the rigid-axle type, so that the wear of the track and wheel flanges will be reduced, while the lateral flexibility of the axles will prevent "corrugation" * of the track rails.

In order that the transverse movement of the axle shall not be restricted by the motor suspension-bars, the latter are arranged with a swinging suspension (see Figs. 256 and 261).

The swing-axle feature has been recently applied by the J. G. Brill Co. to their 21 E truck. In this case the axle-boxes are provided with side extensions, from which the axle-box springs are carried by swing links. A view of the truck is shown in Fig. 258, and a drawing of the swing-link device is given in Fig. 259. It will be observed that the axle-box springs are each carried in a special spring-cap, which is suspended, by a pair of links, from the side extensions of the axle-boxes.

The term "**radial-axle truck**" is applied to a truck with two axles, in which the latter have a limited amount of angular motion in a horizontal plane, independent of the truck frame, thereby enabling a truck with a long wheel base to operate on curves of short radius. With such a truck, therefore, it is possible to use long cars without having to adopt bogie trucks.

Two general principles have been adopted in the designs for radial-axle trucks—one in which the axle-boxes are given freedom for movement in the side-frames, by being suspended from certain points in the main truck frame; and the other in which two sub-trucks, each equipped with an axle and axle-boxes, are pivoted to the main truck frame. Trucks built on the former principle are less complicated than those of the sub-truck type, but do not possess such good radiating properties on sharp curves. Radial-axle trucks without sub-trucks have been developed by the J. G. Brill Co. and the Peckham Truck Co.,† while the latter firm has successfully developed a radial-axle truck of the sub-truck type.

The **Peckham radial-axle trucks** are illustrated in Figs. 260, 261,

* Transverse corrugations of small depth are formed in the head of the track rails by the transverse movement of the wheels across the rail head. Other conditions, such as weight carried on the axles, diameter of wheels, &c., also influence the formation of corrugations. See *The Electrician*, vols. 59, 60, 61, 68, 69, 72 for discussions on the subject.

† For particulars of other radial-axle trucks see *The Engineer*, vol. 113, p. 412; *Tramway and Railway World*, vols. 23, pp. 20, 357; 26, pp. 106, 108, 196, 402; 27, pp. 112, 196, 277; 28, p. 119; 30, p. 98; 34, p. 42.

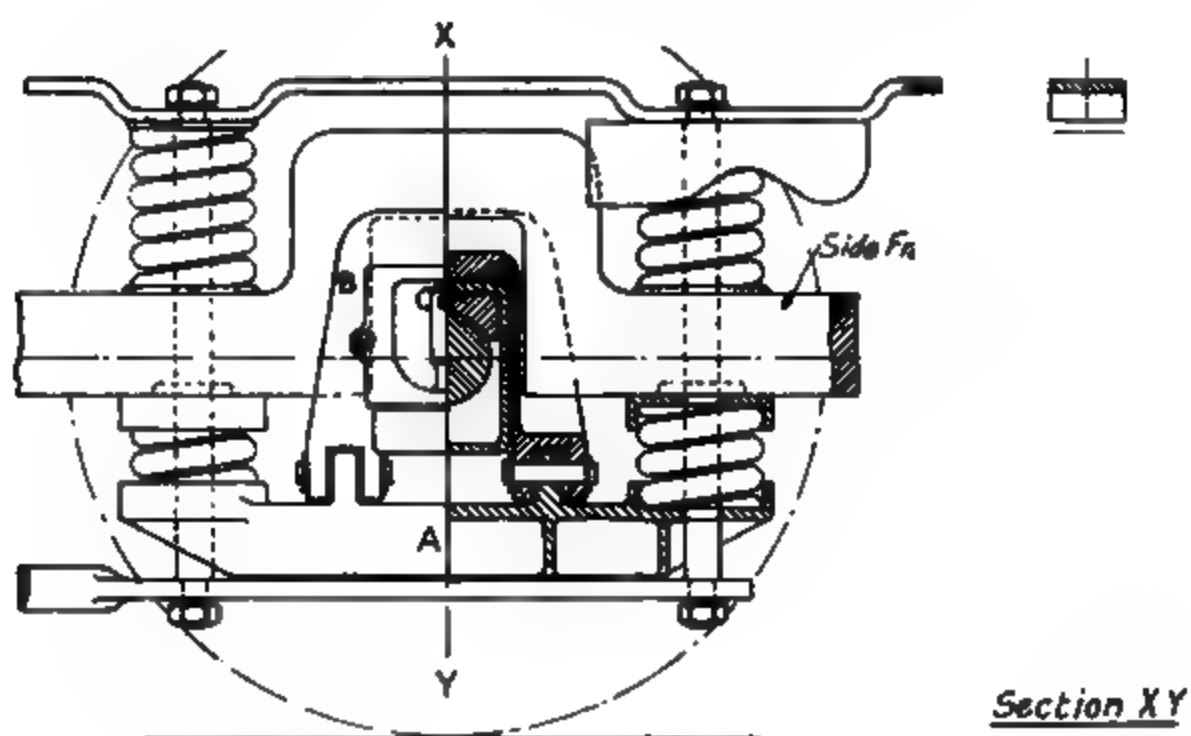


FIG. 257.—Detail of Swing-axle Device for Peckham "P 22" Truck.

End View

Plan

FIG. 259.—Detail of Swing-axle Device for Brill "21 E. S.L." Truck.

FIG. 260.—Peckham "R 24" Radial-axle Truck.

FIG. 262.—Peckham "R. E." Radial-axle Truck.

262, of which Figs. 260, 261 refer to a truck without sub-trucks, and Fig. 262 refers to a truck with sub-trucks. In these trucks the side-frames are provided with wide yokes (or pedestal jaws), so that the axle-boxes can move longitudinally as well as laterally.

The car-body is attached to the top plates in the same manner as with the trucks described above, but the thrust is taken by special blocks bearing against the upper part of the yokes.

FIG. 261.—End View of Peckham "R 24" Radial-axle Truck, showing swinging motor suspension-bar and brake gear (Brush Electrical Engineering Co.).

In the truck shown in Figs. 260, 261, the axle-boxes are provided with side lugs, from which the supporting frames (which carry the main truck frame) are suspended by links with hemispherical ends. The motor suspension-bars are hinged to the truck frame to allow for the movement of the motor frames (corresponding to the movement of the axle). This method of suspending the truck frame from the axle-boxes allows the wheels and axles to adjust themselves to the curvature of the track, so that the axle can take up a position approximately radial to the curve. In this position of the axle the links take up an inclined position, and consequently a couple is brought into operation by means of which the links are restored to their normal (vertical) position when the car leaves the curve. The brake gear is shown in detail in Fig. 261, and is a modification of the standard brake gear for single trucks, with features to allow for the angular movement of the wheels.

The Peckham radial-axle truck with sub-trucks is shown in Fig. 262. In this truck the axle-boxes are fixed to two sub-trucks, which carry the motors and the brake gear. The main truck frame is carried on supporting frames (as in other Peckham trucks), which are suspended from the axle-boxes by swing-links, the latter being hinged to short carriages, provided with roller bearings, on which the supporting frames are carried. Thus the supporting frames have a limited longitudinal movement as well as a transverse movement, so that the axles can adjust themselves to the curvature of the track. In order that the radial movement of the axles shall not be restricted by the swing-links, the latter are hung from swivel-seatings on the top of the axle-boxes.

The inner ends of the sub-trucks are each provided with radius links, which engage rollers fitted to the cross frames and located in the centre line of the main truck frame. The sub-trucks are also connected to the main truck frame at these points by springs, which provide the restoring force for returning the sub-trucks to their normal position.

On account of the radius links and the method of supporting the truck frame from the axle-boxes, the sub-trucks are able to take up a radial position on curves of short radii. The minimum radius of curve which can be negotiated with the axles in the radial position depends on the wheel-base of the truck and other features. With the present designs of Peckham radial-axle trucks, curves of 30 ft. radius can be negotiated by a truck with a wheel-base of 10 ft., the axles being in the radial position.

The **Brill radial-axle truck** is of the swing-link type, with two fixed pivotal points (one for each axle) on the centre-line of the truck, the pivotal points being attached to the motor suspension-bars, thereby avoiding the use of sub-trucks. The truck is shown in Fig. 263.

The side frames are supported on swinging links which are hung from springs located in "wings" on the axle-

FIG. 263.—Brill "Radiax" Radial-axle Truck.

boxes. These links have the upper end in the form of a hemispherical head, and have two pins fixed in the lower end, the pins engaging in grooves formed in the lower part of the frame yokes. Under normal conditions the links are vertical, and each pin has a full bearing in its groove. When the axle is deflected, the links take up an inclined position, in which one pin in each link leaves its groove. In this position of the links the weight of the car, acting on the pins, exerts a couple tending to restore the links to the normal position. By means of the motor-frames and the suspension bars the axles are pivoted to two king pins, which are fixed to the cross frames and are located on the centre line of the truck.

When the car is rounding a curve, the centrifugal force acting on the car-body is transmitted to the king pins, and the truck frame—being capable of lateral movement—is displaced slightly outwards, thereby causing the axles to take up a position approximately radial to the curve.* The radiating action will, of course, be better at higher speeds than at low speeds, and the use of the special type of swinging link ensures that the axles will return to the normal position when the car leaves the curve.

The brake-gear is arranged to radiate with the axles by means of floating and equalising levers, the supports for the brake-block links being carried on extensions of the motor suspension-bars.

The truck is built with a wheel-base of from 8 ft. to 12 ft., and is suitable for car-bodies which do not exceed 36 ft. over the platforms. With a standard wheel flange and a $1\frac{1}{2}$ in. groove in the rail, the truck with the shorter wheel-base will negotiate a curve of 29 ft. radius as satisfactorily as a rigid-axle truck with a wheel-base of 4 ft. $1\frac{1}{2}$ in.

The following particulars refer to a truck having a wheel-base of 10 ft. (suitable for a car-body 32 ft. overall) :—

Gauge	4 ft. 8 $\frac{1}{2}$ in.
Spring base of car-body springs	18 „ 10 „
Length over top plates	19 „ 4 „
Width over top plates	6 „ 3 „
Width overall	7 „ 3 „
Diameter of wheels	30 „
Height from track rail to top plates with empty car-body in position	2 „ 1 $\frac{1}{8}$ „
Weight without wheels and axles	4000 lb.
Minimum radius of curve for continuous operation	38 ft. 0 in.
Equivalent wheel base of rigid-axle truck to negotiate curve as satisfactorily as radial-axle truck (see above)	5 „ 5 „

Two types of **bogie-trucks** are adopted for electric traction, viz. (1) the maximum-traction truck (also called a single-motor truck), having wheels of unequal diameter—the use of which is exclusive to

* The long swing-links will permit a considerable radial movement of the axles without the links assuming an excessive inclination, while the arrangement of the pins at the bottom of the links ensures that the car-body will be held steady on straight track.

tramways—and (2) the equal-wheel bogie-truck, which is principally used on railways and is described in Chapter XVI.

In the latter type of truck the load is supported on a bolster placed midway between the axles, and is therefore distributed equally between them. If only one axle is equipped with a motor, it is apparent that only one-half of the load on the bolster will be available for adhesion.* By supporting the load nearer to the driving axle, a larger portion of it can be utilised for adhesion, and consequently a greater tractive-effort can be exerted by the driving wheels before slipping occurs. The practical limit is reached when about 75 per cent. to 80 per cent. of the total weight of the car (i.e. the car-body, trucks, and electrical equipment) is placed on the driving axles, and trucks constructed on this principle are known as the **maximum-traction type**.

FIG. 264.—Maximum-traction Swing-bolster Bogie Truck, as adopted on the London County Council Conduit Tramways.

Under the usual tramway conditions, where only two motors are employed on a car, it is evident that this type of truck is more suitable than the type in which the load is carried on a central bolster. In cases where large cars, on bogie trucks, are required to operate on gradients exceeding 1 in 15, it is necessary to have the whole of the weight available for adhesion, and equal-wheel bogie-trucks, each equipped with a pair of motors (i.e. a four-motor equipment), must be used.

In all modern types of maximum-traction trucks the car-body is supported on a "**swing-bolster**," and in some cases the pivotal point or swivelling centre is displaced from the centre of the bolster towards the driving axle. The radiation of the driving wheels (that is, the transverse movement of the wheels relative to the car-body when the car is rounding a curve) is thereby reduced, thus allowing the side-sills of the car to be carried low, with a consequent reduction in the height of the platforms and floor. With this type of truck the pony wheels (which term is applied to the trailing wheels of the truck) must be

* The load on the driving axle will also include one-half of the weight of the truck and the component of the weight of the motor which is not carried on the suspension springs.

smaller in diameter than the driving wheels, in order that the former may clear the side-sills when the truck radiates.

A truck in which the above features are embodied, and which has been standardised on the London County Council tramways, is illustrated in Fig. 264. The side-frames are of cast steel, and are connected together by four channel steel sections, one at each end and two in the centre. The centre channels are called the **transoms**, and are fixed thus:] [. Another channel section (arranged thus: U) is suspended under the transoms by two pairs of swing-links,* as indicated diagrammatically in Fig. 265. This section, which is called the **spring plank**, carries the springs upon which the bolster is supported, while the springs supporting the truck frame are carried on the top of the axle-

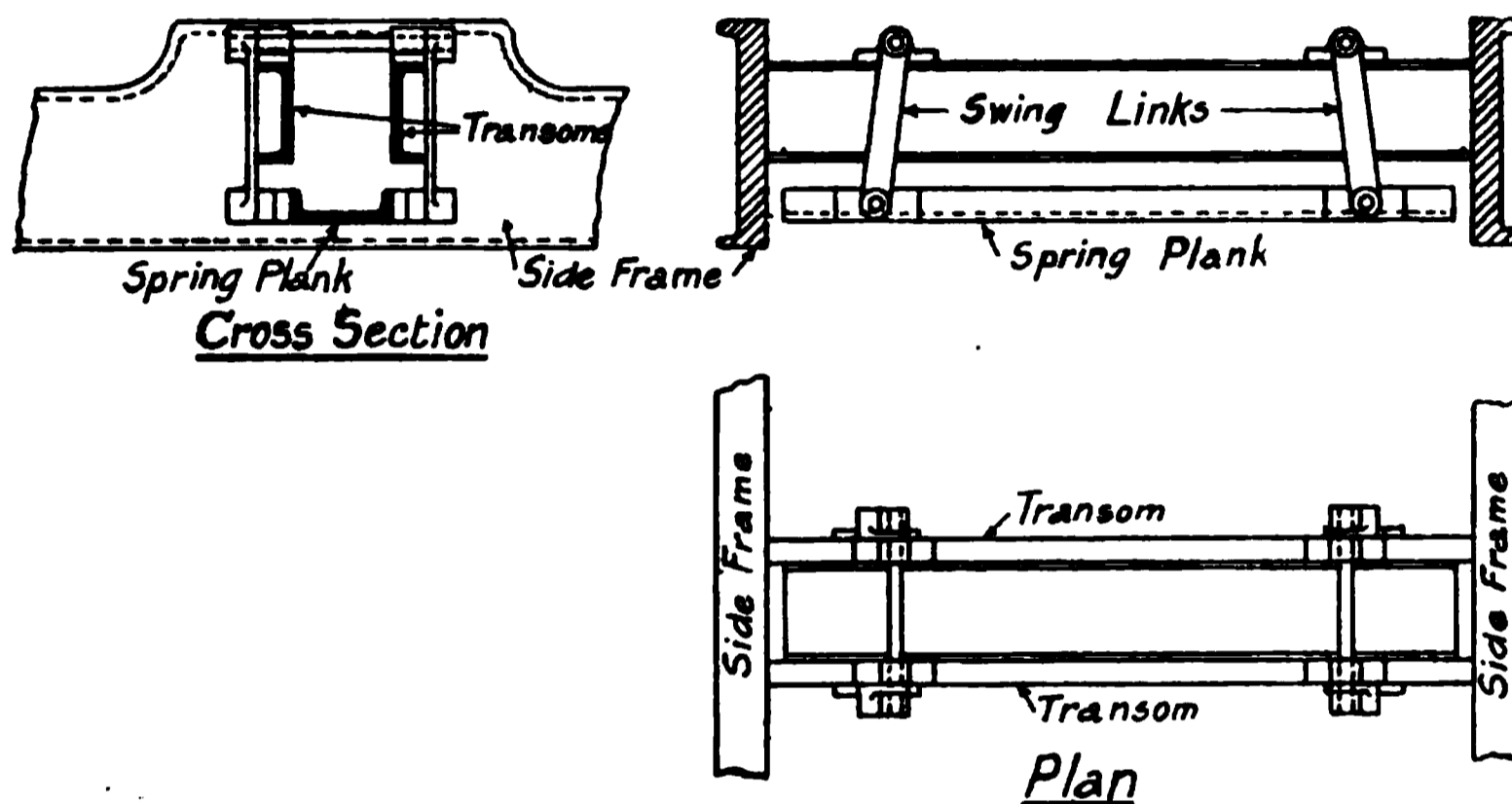


FIG. 265.—Arrangement of Transoms, Swing-links, and Spring Plank in Maximum-traction Swing-bolster Bogie Truck.

boxes. The cast-steel bolster is a sliding fit between the transoms, and performs the double function of supporting the car-body and of transmitting thereto the thrust from the truck. The car-body is not permanently fixed to the bolster, but is connected to it by a **king pin**, which forms the **swivelling centre** of the truck. In the present case the king pin is displaced from the centre of the bolster towards the driving axle, so that it is necessary to adopt a swivel- or radius-plate for the centre bearing. The upper portion of this swivel plate (which can be seen in Fig. 264) carries the king pin, and is fixed to the underframe of the car-body, while the lower portion rests in a spherical seat on the bolster. The car-body is also supported by **side bearings**, which are formed by a projection at each end of the bolster engaging bearing plates fixed to the underframe. In order to prevent excessive side-swaying of the car, the oscillation of the bolster is limited by the suspension pins of the swing-links extending across the tops of the transoms.†

* The object of the swing-links is: (1) to allow the bolster to swing slightly outwards when the car negotiates a curve, thereby relieving the car-body and truck from strains which would otherwise be produced, and (2) to give easier riding to the car.

† See *Tramway and Railway World*, vol. 38, p. 270, for details of a truck with the Peckham swing-axle feature.

As the wheel base of the truck is only 4 ft. 6 in., it is apparent that the motor cannot be placed between the bolster and the driving axle. Therefore the motor must be placed in the "outside" position, with the suspension bar resting on springs which are carried on brackets fixed to the end frame. This position of the motor is a characteristic feature of all maximum traction trucks of the bolster type, and a little consideration will show that it results in a reduction of the load (due to the car-body and truck) on the pony wheels. As the position of the bolster is governed by the diameter of the driving wheels, it is generally necessary to carry at least 40 per cent. of the weight of the car-body on each pair of pony wheels, and consequently there is always sufficient load on these wheels to compensate for the lifting action of the motor.

It will be observed in Fig. 264 that the side-frames are fitted with two extensions, which are connected together by two steel channels. These extensions are only fitted to one of the trucks on a car, and are for the purpose of carrying the plough collector.

FIG. 266.—Brill "39 E" Maximum-traction Swing-bolster Bogie Truck.

The truck is also shown equipped with a magnetic track-brake, which is arranged to operate the wheel brakes in the manner described below. The wheel brakes, however, can be operated independently of the track brakes in the usual manner.

The wheel-base of the truck is 4 ft. 6 in., the centre of the bolster is 2 ft. from the centre of the driving axle, and the swivelling centre is displaced 1 ft. 5 in. from the bolster towards the driving axle.

Another type of **swing-bolster maximum-traction truck** is illustrated in Fig. 266. This truck (known as the **Brill 39 E**) differs in several features from the truck last described. Firstly, the pivotal point is at the centre of the bolster; secondly, there is no spring plank; and, thirdly, the bolster is provided with a graduated spring system which gives easy riding at all loads.

The side-frames are of forged steel, and rest on spiral springs placed on the top of the axle-boxes. The transoms are of angle steel, and are bolted to gusset plates fixed to the upper chord of the side-frames. Elliptical swing-links are carried from the side-frames at each side of the transoms, and these links support the ends of semi-elliptic springs, from which the bolster is supported. In the earlier forms of this truck the bolster was fixed directly to these springs, but in the truck under consideration a short spiral spring, in special caps, is interposed between each end of the bolster and the semi-elliptic springs. The caps—in

which the spiral springs are placed—are about $\frac{3}{8}$ in. apart when the unloaded car-body is in position. When the car is about half-loaded with passengers the spiral springs are compressed, so that the caps come into contact, thereby transferring the load entirely to the semi-elliptic springs.

The bolster is of cast steel, and is connected to the lower spring caps (which are fixed to the centre of the semi-elliptic springs) by links, thereby relieving the spiral springs from side thrusts and also preventing the semi-elliptic springs from twisting when the bolster swings over. The bearings for the king pin and car-body are fitted to the top of the bolster, while to the sides are fitted chafing (or bearing) plates, which engage similar plates fitted to the transoms.

The truck is built with a 4 ft. 6 in. wheel-base, the centre of the bolster being 1 ft. 11 in. from the centre of the driving axle. The

FIG. 267.—Arrangement of Brake Gear on Brill "39 E" Maximum-traction Bogie Truck.

diameter of the driving wheels may be from 30 in. to 34 in., while that of the corresponding pony wheels is 19 in. to 23 in. The weight of the truck (without wheels and axles) for standard gauge is 2750 lb.

The brake gear for a maximum-traction truck differs from that for a truck with a central bolster, in that *unequal pressures must be applied to the brake shoes on the driving and pony wheels*, the pressures being in the ratio of the loads carried on the wheels. In the truck under consideration this is accomplished by a differential lever system with brake-beams for both sets of wheels, which ensures the alignment of the brake shoes on each pair of wheels.

The arrangement of the levers and brake-beams is indicated in Fig. 267. The brake shoes for the driving wheels are suspended from brackets fixed to one of the transoms, while those for the pony wheels are suspended from brackets fixed to the upper chord of the side frames. The brake-beams *B*, *C* are operated by a central lever *A*, to which is connected a pull-rod *K* from a floating lever attached to the centre of the underframe, the pull-rods from the brake spindles on the platforms being also connected to this floating lever, so that the radiation of the trucks does not interfere with the operation of the brakes. The central lever *A* is connected to the brake-beam *B* by the link *D*, and its

lower end is connected by the adjustable rod *E* to the differential lever *F*, which has a fulcrum on the cross-bar *G*, fixed to the lower chords of the side-frames. The upper end of the differential lever is connected to the pony wheel brake-beam *C*. When a tension is applied to the pull-rod *K*, the lever *A* turns about the pin *L* and applies the brakes to the driving wheels. As soon as these brakes are applied the lever has a fulcrum at the pin *M*, and a force is transmitted through the rod *E* to the differential lever and brake-beam *C*, thereby applying the brakes to the pony wheels.

Position of pony wheels for cars with bogie trucks.—In all the above types of maximum traction trucks the running of the truck is satisfactory whether the pony wheels are leading or trailing. Since tramcars must be suitable for running in either direction, the trucks are arranged symmetrically about the centre of the car, with the pony wheels either towards the centre or towards the platforms. The latter position is standard for American practice,* and the pony wheels are arranged under the platforms, thereby giving a better support for these portions of the car. In this country, however, the space under the platforms is required for the life guards, and, unless the platforms are very long, the car-body will be supported better with the pony wheels towards the centre of the car. Generally the arrangement of the trucks will be influenced by the design of the underframe, and, in a given case, the trucks should be arranged to provide the best support for the car-body and the platforms. These are probably the reasons for the apparent diversity of opinion among some car builders, in consequence of which there are numerous examples of cars with the pony wheels towards the centre and towards the platforms. In the case of conduit tramways, it is the practice to support the plough from an extension of the truck frame (see Fig. 264), and under these conditions the trucks must be arranged with the pony wheels towards the centre of the car.

The considerations which affect the diameter of the driving wheels have already been discussed in Chapter IV. Until recently the standard diameter for these wheels was 30 in., but the introduction of larger motors and steel tyres necessitated the use of wheels having a minimum diameter (when new) of $31\frac{1}{2}$ in. In America, however, the standard diameter is 33 in., but with some types of centre-entrance cars it has been necessary to adopt a diameter of 24 in.

Two types of wheels are in use on tramways, viz. (1) the chilled cast-iron wheel (which is a relic of horse tramways), and (2) the steel-tired wheel with a steel centre. In the first type the thickness of the "chill" is about $\frac{3}{4}$ in., and the wheels must be scrapped when this amount of wear has taken place. The guaranteed life is 30,000 miles, but there are records of wheels of this type averaging 40,000 to 60,000 miles.†

The second type of wheel is made with the centre either of cast steel or of forged steel, and has the advantage that the centre seldom

* With the centre-entrance cars, the trucks have to be arranged with the pony wheels towards the centre of the car.

† For some comparative tests on the durability of brake shoes and tyres see a paper (by Mr. W. J. Dawson) presented to the 1910 Annual Conference of the Municipal Tramways Association. See *The Electrician*, vol. 65, p. 1010.

requires renewing. This wheel is more costly at the outset than the "chilled" wheel, but the average cost over a number of years will be lower. The tyres are usually 2 in. to $2\frac{1}{2}$ in. thick at the tread; they are shrunk on to the centres and secured in position by set-screws or retaining rings. The steel from which the tyres are manufactured is exceptionally hard, but at the same time it is tough and ductile, the tensile strength being approximately 50 tons per sq. in. With tyres $2\frac{1}{2}$ in. thick a wear of from $1\frac{1}{2}$ in. to $1\frac{3}{4}$ in. radially can be allowed, which will give a life of from 60,000 to 100,000 miles, the guaranteed life being usually based on a radial wear of $\frac{1}{8}$ in. for every 5000 miles. These figures, of course, will be affected by the curvature of the track, since, if the curves are all in one direction, the tyres of the wheels on one side of the car will be worn at a greater rate than those on the other side.

The average weight of a chilled cast-iron wheel (30 in. in diameter) is 300 lb., while that of a steel-tyred wheel ($31\frac{1}{2}$ in. in diameter) is 350 lb.

BRAKES

The importance of brakes on an electric tramcar cannot be over-estimated, and they should be given quite as much attention as the electrical equipment. All cars must be equipped with hand brakes, in which the brake shoes act on the rims of the wheels, while cars which have to operate on steep gradients must be equipped also with track brakes. In the case of large tramway systems, operating through

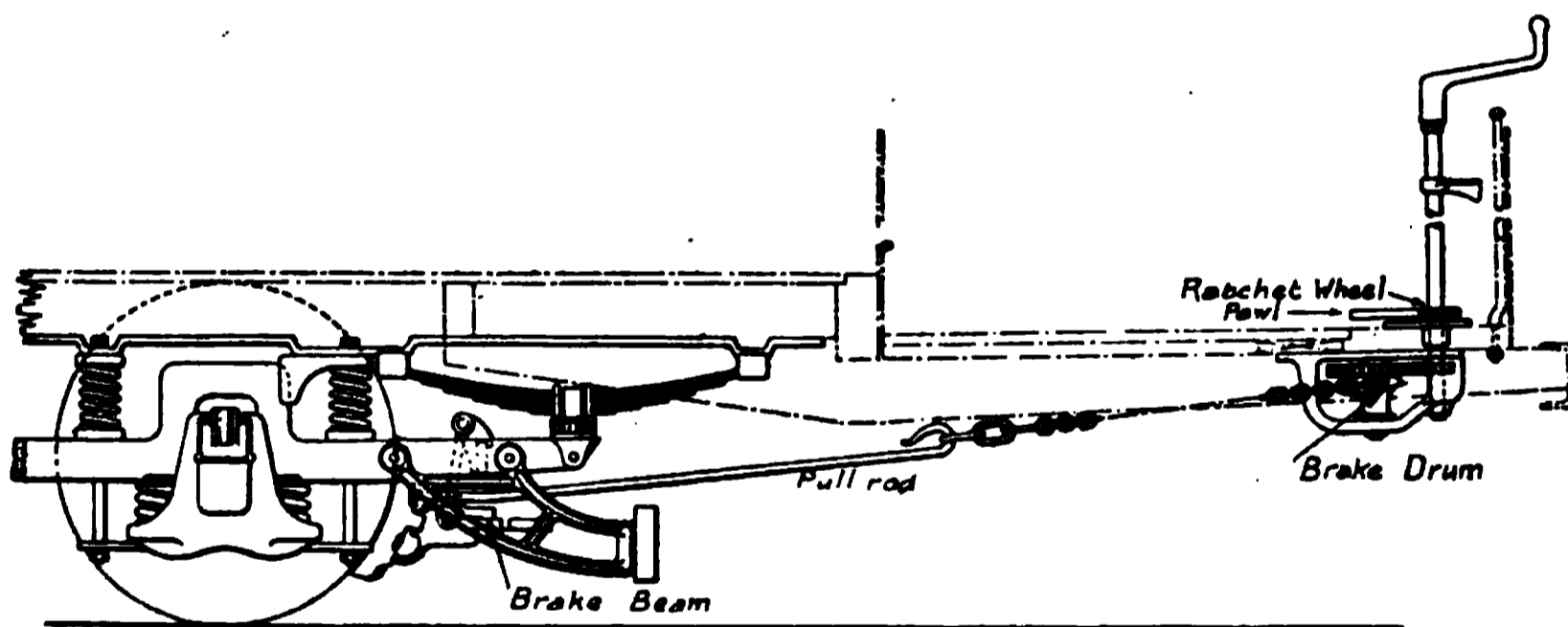


FIG. 268.—Arrangement of Platform Gear for Wheel Brake on Single-truck Car.
(A Peacock quick-acting geared brake drum is shown.)

congested traffic, the maximum speed is fixed by the Board of Trade, and is based on the brake equipment. Therefore cars equipped with powerful and quick-acting brakes can be run at higher schedule speeds than those not so equipped. This point is of the utmost importance on a system like the London County Council tramways, where competing petrol motor-buses are run over practically the same routes as the tramcars.

The principal types of brakes in use on tramcars are : (1) the wheel (or hand) brake, which acts on the wheels only ; (2) the rheostatic electric brake, in which the motors are converted into generators and are loaded on rheostats, the brake being applied and regulated from the controller (see Chapter VIII, p. 147) ; (3) the mechanical track

brake, applied by hand from hand-wheels on the platforms of the car; (4) the magnetic track brake, with or without an attachment for operating the wheel brakes, the current for the excitation of the magnets being derived from the motors.

The air brake, although used extensively in America, has not been adopted in this country, on account of the additional equipment required on the car. Moreover, the speeds and traffic conditions here do not warrant the use of this type of brake.

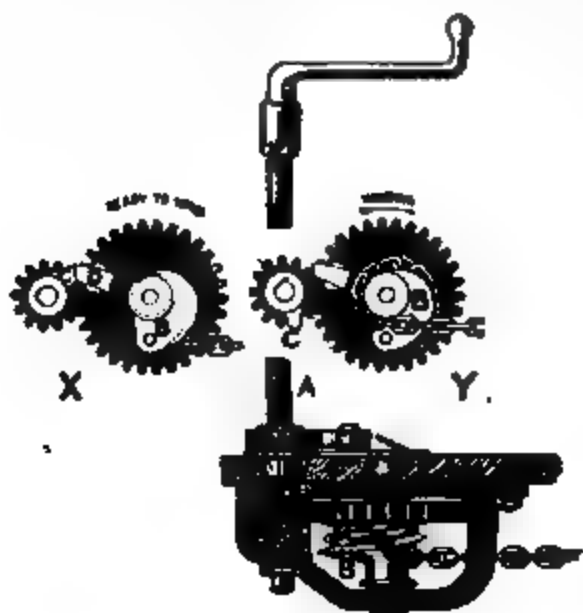


FIG. 268a.—Peacock Quick-acting Brake.

The wheel brake, applied by hand, is a relic of the horse tramcars, with improvements introduced to obtain a greater braking force and a more rapid application of the brake. The portion of the brake associated with the truck has been dealt with above (see p. 303), so that it is now only necessary to consider the operating gear on the platforms. The pull-rods from the brake levers are connected to the brake drums on the platforms by a short length of chain, as shown in Fig. 268. The brake is applied by winding this chain around

the brake drum, and unwinding is prevented by means of a ratchet-wheel and pawl on the operating spindle.

In the Peacock quick-acting brake the drum consists of a grooved cam *B*, Fig. 268a, which is geared to the operating spindle *A*. The pinion and gear wheel are fitted with stops *C, D*, which are in contact when the brakes are "off" (see diagram *X*, Fig. 268a). These stops prevent the brake drum from over-running when the brakes are released, and ensure that the drum is stopped in a position from which the recovery of the chain is most rapid. Thus during the application of the brakes all unnecessary winding is avoided, and, by the adoption of a cam-type brake drum, a quick action is obtained. The gearing enables a powerful braking effect to be obtained without excessive exertion from the motorman.*

For cars weighing from 12 to 15 tons it is general practice to adopt a gear ratio of 39/12, which, with the standard 10½-in. operating handle, gives a leverage of 22 between the handle and the chain.

With an effort of 50 lb. applied to the handle, the resulting tension (corrected for friction) in the brake chain is 983 lb.

FIG. 269.—Magnet of B.T.-H. Track Brake.

* For details of a combined wheel and track brake, see *Tramway and Railway World*, vol. 23, p. 111.

The **mechanical track brake** * is of the slipper type, and usually consists of one or more pairs of wooden blocks, which are pressed on to the track by means of levers, or screws, operated from a handwheel on the platform. This brake is intended for use on steep gradients, and utilises a portion of the weight of the car as the braking force. The wheel brakes can, of course, be applied at the same time, but in order to render these brakes operative it is necessary to design the hand-wheel and levers of the track brake so that sufficient weight is carried on the wheels to prevent them skidding when the brakes are applied.

FIG. 270a.—Westinghouse Magnetic Track Brake applied to a Single Truck.

FIG. 270b.—Westinghouse Magnetic Track Brake applied to a Maximum-traction Bogie Truck.

Of **magnetic track brakes** there are three types available (known as the Westinghouse, the British Thomson-Houston, and the Maley brakes). Each type consists of a special slipper brake which is in the form of two or more electromagnets. The latter are energised from the car motors and are thereby attracted to the track rails, the drag or thrust of the magnets being transmitted to the truck frame, and, in some cases, to the shoes of the wheel brakes. In the latter case we have a combination of three brakes [viz. (1) a track brake, (2) a wheel brake, and (3) an electric brake, produced by the retarding torque due to the motors acting as generators] which are all acting simultaneously, and consequently

* See *The Tramway and Railway World*, vol. 29, p. 229, for particulars of a mechanical track brake (for centre-slot conduit tramways) which has been adopted by the London County Council Tramways on exceptionally steep gradients (1 in 10). For further particulars of Mechanical Track Brakes see *The Tramway and Railway World*, vol. 35, p. 355.

it is possible to obtain a very high retardation.* Since the action of the brake is dependent upon the revolution of the driving wheels, means must be taken to prevent these skidding when emergency applications are made.

The **electromagnets** for the Westinghouse and British Thomson-Houston brakes† are of the bi-polar type with elongated pole faces, which are arranged longitudinally with the rail head and a short distance apart. A typical magnet is illustrated in Fig. 269. The body of the magnet is of cast steel, and the renewable pole faces are of soft steel. The excitation is supplied by a single coil, which is enclosed in a water-tight metal case.

The magnetic circuit is transverse to the rail head, so that the flux is not limited by the section of the rail head—as in the original design of the Westinghouse magnet, in which the magnetic circuit was longitudinal with the rail. Although the leakage is greater with the present arrangement of the pole faces, several advantages are obtained over the original Westinghouse design. Thus the vertical force between the magnet and the rail can be arranged to suit the class of car (*e.g.* by altering the length of the pole faces), while a much simpler attachment is required for transmitting the thrust to the truck and the wheel brakes.

In the **Westinghouse** design of magnetic track brake, the magnet is arranged to operate the wheel brakes in addition to transmitting its thrust to the truck frame. The attachment for operating the wheel brakes in the case of a single rigid-axle truck is indicated diagrammatically in Fig. 270*a*, while a portion of the attachment for a maximum traction truck is shown in Fig. 270*b*.

Referring to Fig. 270*a*, it will be seen that the magnet is suspended from the side-frame of the truck by spiral springs, which are adjusted so that the pole faces are about $\frac{1}{4}$ in. above the rail. The magnets on opposite sides of the truck are connected together by two cross bars which are bolted to projections on the inner pole pieces, while two other projections on these pole pieces engage the tail of a thrust lever pivoted to each side-frame, the upper end of this lever being in the form of a cam. Connecting-rods—attached to each of the brake-beams—are provided with specially formed ends to fit over this cam, so that any movement of the thrust lever from the vertical will cause the cam to apply a tension to each of the connecting-rods. The brake shoes will therefore be applied, and the pressure of the shoes on the wheels will depend on the drag of the magnet. This drag will depend on the exciting current, which, for a given position of the controller, will vary with the speed of the car. Hence the pressure of the brake shoes on the wheels will be greater at high speeds than at low speeds. Now these are the conditions that must be satisfied to avoid skidding of the wheels, so that, under normal conditions, the operation of the wheel brakes from the track brake will be satisfactory.

When emergency applications are made at high speeds there is a

* Under emergency conditions a retardation of 12 ft. per second per second can be obtained. For service applications the retardation should be limited to from 2 to 3 ft. per second per second.

† Standard Westinghouse magnets are used with the Maley brake. This brake only differs from the above types in the manner in which it is mounted and operated. See *The Electrician*, vol. 60, p. 240, for details.

possibility of the wheels skidding if the brake is applied too quickly, as under these conditions the motors will build up to a high voltage and produce a large current in the brake circuit.*

The heavy application of the wheel brakes, combined with the large retarding torque on the motors, will produce a braking force which may be in excess of the maximum value permissible. Under these conditions the wheels will skid, thereby rendering the brakes ineffective. In order to avoid this, a skid-proof attachment has been developed. This consists of solenoid-operated switches (see Fig. 271) in the brake circuit, which connect resistances in parallel with the fields of the motors when the current in the brake circuit exceeds certain values.

The brake can also be fitted with mechanical operating gear, so that it can be applied by hand in a manner similar to that described below.

In the **British Thomson-Houston** track brake the magnets are suspended from the side-frames in a manner similar to that described above, and the thrust is transmitted to the truck through special thrust brackets. The brake is applied only to the track rails, but it is designed for both mechanical and electrical operation.

The mechanical operating gear is shown in Fig. 272, and consists of a toggle joint which is formed by a compression link attached to the magnet and an adjustable link hinged to the thrust bracket. The toggles of each brake are operated, through chains, from a floating lever, which is supported from a suitable bracket attached to the under-frame of the car, the floating lever being operated through pull rods from handwheels on the platforms.

It will be noted that each of the above types of magnetic track brakes is arranged for mechanical operation. This is desirable where steep gradients have to be negotiated, as it enables the brake to be applied before the car starts the descent, and, moreover, it renders the brake operative if there should be an open-circuit or bad connection in the brake circuit.†

The excitation of the brake magnets from the car motors is considered to be more reliable than obtaining the excitation from the trolley wire, as the brake is thereby rendered independent of the generat-

FIG. 271.—Solenoid-operated Switches for use with Westinghouse Magnetic Track Brake (Skid-proof Type).

* The resistance in the brake circuit at each notch of the controller is the same at all speeds, and must be arranged so that the brake is effective at low speeds (e.g. 4 m.p.h.).

† Some serious accidents have happened due to the failure of the brake from these causes. See Board of Trade reports in *The Electrician*, vols. 58, p. 102; 61, pp. 402, 913.

ing station or the position of the trolley wheel. On the other hand, it is necessary to prevent the wheels becoming locked, due to the misuse of the hand (wheel) brake. In order to remove this danger the wheel brakes have been removed from the cars equipped with the Maley brake.

With the present design of the bi-polar track-brake magnet an exciting current of 20 amperes will produce (in one size of magnet) a

PLAN

FIG. 272.—Mechanical Operating Gear of B.T.-H. Magnetic Track Brake.

vertical force of 2 tons between the pole faces and the rail, while with 5 amperes a force of nearly one ton is produced.* It is evident therefore that this brake, when combined with the wheel brakes in the above manner, can be used as a service brake without producing an excessive temperature rise of the motors. The increased retardation will then allow of an increase in the schedule speed, and in many cases it will be possible to operate at a higher maximum speed (due to the more efficient

* See a paper on "Electric Braking on the Glasgow Tramway System" by A. Gerrard (*Journal of the Institution of Electrical Engineers*, vol. 45, p. 399).

braking equipment) than when the hand brake is used for service stops.

The force of attraction or "pull" of any magnet on its armature is given by the fundamental equation $f = \frac{B^2 A}{8\pi}$, where **B** is the flux density at the pole face (expressed in C.G.S. units and assumed to be uniform), *A* is the area (in square cms.) of the pole faces in contact with the armature, and *f* the force of attraction in dynes.

Converting *f* into tons weight, and *A* into square inches, we have $f \text{ (tons)} = \left(\frac{B^2 A}{3.9} \right) 10^{-9}$. For **B**=15500—which corresponds to a moderate saturation with cast steel— $f=0.0616$ tons for each square inch of pole face area. Thus, at this flux density, the pressure between the magnet and the rail will be 138 lb. per sq. in.

CHAPTER XVI

ROLLING STOCK FOR ELECTRIC RAILWAYS (Motor-coach Trains)

CONSIDERATIONS of energy consumption will show that it is desirable to use motor-coach trains for urban and suburban traffic. When the terminal conditions are considered, however, other advantages of motor-coach trains will appear. Thus, since the capacity of a terminus is limited by the number of trains which can be got into and out of the station in a given time, it is apparent that with motor-coach trains the capacity of the terminus will be much greater than that which can be obtained with locomotive-operated trains, on account of the smaller number of signal and other movements required for the former trains. Moreover, locomotives will require siding accommodation.

A further advantage of motor-coach trains is that the train can be made up to suit the traffic with a minimum of shunting operations.* If the train weight per motor is maintained constant, then the trains for light and heavy traffic will be able to maintain the same schedule speed with the same specific energy consumption.

The **adhesive weight, with motor-coach trains**, is equal to the total load on the axles which are equipped with motors. In trains made up with all motor-coaches and all axles equipped with motors, the adhesive weight will be equal to the total train weight. On some railways in this country, however, it is the practice to operate one motor-coach with one, two, or three trailer coaches as a *train unit*, and to run the service with trains made up of one unit, or of two or more units coupled together, as demanded by the traffic. In these cases it is necessary that the adhesive weight should be at least 25 per cent. of the total train weight (generally it is from 33 per cent. to 50 per cent.), while, to avoid slipping of the driving wheels under unfavourable conditions of weather, the total accelerating tractive-effort should not exceed about 15 per cent. of the adhesive weight. The adhesive weight and total train weight of some typical motor-coach trains are given in Table XI, while further particulars of the motor-coaches are given in Table XII (p. 349).

* A striking example of the rapidity with which electric trains can be made up at a terminus has been given by Mr. J. Shaw (General Manager of the Mersey Railway) in a paper entitled "The Equipment and Working Results of the Mersey Railway under Steam and Electric Traction" (*Minutes of Proceedings of the Institution of Civil Engineers*, vol. 179, p. 19).

In the paper it is stated that the trains are allowed three minutes at the termini, during which interval any alteration in the make-up of the train has to be done. The average time for making up a train is two minutes, which includes shunting and coupling of brake and electric connections.

TABLE XI

ADHESIVE WEIGHTS OF TYPICAL MOTOR-COACH TRAINS

Railway.	Weight of one Motor-coach without Passengers.	Number of Motors per Motor-coach.	Weight of one Trailer-coach without Passengers.	Number of Passengers.		Composition of Train.	Total Weight of Train.		Adhesive Weight of Train.		Ratio:— Adhesive Weight to Total Weight.	
				Motor-coach.	Trailer-coach.		Without Passengers.	With Full Number of Passengers.	Without Passengers.	With Full Number of Passengers.	Without Passengers.	With Full Number of Passengers.
Metropolitan District } (London)	Tons. 33	2	Tons. 22	48	48 {	2M, 2T 3M, 4T	Tons. 110 187	Tons. 122 208	Tons. 41.1 61.6	Tons. 44.15 66.1	0.374 0.33	0.36 0.318
Metropolitan (London) } (Saloon stock)	38.5	4	22.5	48	56	2M, 4T	167	187	77	83	0.46	0.444
Metropolitan (London) } (Compartment stock)	38.125	4	19.112	40	64	2M, 5T	171.8	196.8	76.25	81.25	0.444	0.413
Lancashire and Yorkshire } (Liverpool-Southport section)	45.6	4	26.1	69 {	103-3rd 76-1st	2M, 2T* 2M, 3T†	143.4 169.5	163 195.75	91.2 91.2	99.8 99.8	0.636 0.538	0.612 0.51
London and South-Western	36.2	2	21.6	60	70	4M, 2T‡	188	211.8	99.2	105.6	0.528	0.5
London, Brighton and } South Coast }	51.5	4	24.25	70	74	2M, 4T	200	227.25	103	111.75	0.515	0.492
London Electric (tube) } Railways }	27.5†	2	17.75†	36†	48†	2M, 2T	90.5	101.1	37.9	39.4	0.419	0.39

* Including one first-class trailer and one third-class trailer.

† Including one first-class trailer and two third-class trailers.

‡ Centre-entrance, all steel cars.

§ A "train unit" consists of two motor-coaches and one trailer-coach.

Types of Rolling Stock.—Two types of rolling stock have been adopted for motor-coach trains, viz. (1) the compartment type of coach with side doors—similar to the rolling stock on our steam railways—and (2) the saloon type of coach or car * with central and end doors. The latter type of stock was introduced for the early electrifications in this country, and it is the only type permissible for deep-level underground (or tube) railways. Although there exists a considerable difference of opinion among railway engineers as to the advantages of the two types of stock, nevertheless the saloon type, in virtue of its better facilities for the distribution of the passengers when entering the train, is more suitable for urban service with dense traffic than the compartment type. For longer distance suburban traffic, however, the compartment type of coach is generally preferable.

The **maximum length and width of the coaches** which can be used on a given line are determined by the lay-out of the track (which affects the clearance between passing trains), the loading gauge, and the size of the tunnels. When sliding or inwardly-opening doors are adopted—as in the saloon type of coach—the clearance between passing trains can be made smaller than that when outwardly-opening side doors are used.

The length of the coaches for express service on the principal steam railways in this country varies from 50 ft. to 75 ft., while the width varies from 8 ft. to 9 ft. 3 in.

The largest coaches for electric railways in this country are in service on the Lancashire and Yorkshire Railway (Liverpool-Southport section), and have a length of 60 ft., with a width of 10 ft.; they are of the end-door saloon type, with transverse seats, a central corridor, and seating accommodation for 100 passengers. Each of the transverse seats on one side of the corridor is arranged to accommodate three passengers, while on the other side of the corridor two passengers are accommodated on each seat.

The large width of the coach has enabled this arrangement of seats to be adopted with a corridor 2 ft. wide, whereas for a 9-ft. coach and the same width of corridor it would have been possible to seat only four passengers cross-wise, thereby reducing the seating capacity to 82. The increase in the weight of the coach, due to the increase in width, is only that of the floor, roof, and extra seats, and, for the 60-ft. coaches under consideration, is of the order of 15 cwt., or about 93 lb. per extra seat. If the increase in the seating capacity had had to be provided for by additional coaches to the train, the weight would have been of the order of 5 cwt. per extra seat.†

In the design of rolling stock for urban and suburban railways it is important to reduce the weight by the use of suitable materials, as unnecessary weight not only increases the energy consumption but also leads to increased maintenance costs when the whole of the equipment is considered. Of course if the stock is too lightly built it will

* The saloon type of coach, with end doors, is the standard type of passenger rolling stock in America, where all classes of rolling stock are designated as "cars." The term "car" is used to some extent in this country in connection with electric trains, particularly when these are of the saloon type.

† See "The Design of Rolling Stock for Electric Railways" by H. E. O'Brien (*Journal of the Institution of Electrical Engineers*, vol. 52, p. 445). This paper contains some interesting and valuable data on rolling stock.

FIG. 273.—Latest Type of Centre-entrance Motor-car on the London Electric (Tube) Railways. (Built by the Brush Electrical Engineering Co.)

not be sufficiently strong to withstand the stresses due to the high acceleration and braking, and in this case the maintenance costs will be high. But the use of aluminium and steel of high tensile strength will enable the weight to be reduced without sacrificing strength. With the "all steel" type of saloon car it is possible to utilise the sides of the body in conjunction with the sole-bars of the underframe, thereby allowing the latter members to be reduced in section. This type of car, although somewhat heavier than a standard wooden car of similar dimensions, has a considerably lower maintenance cost than the latter.*

The details of the construction of coaches for operating on surface

FIG. 274.—Interior of Centre-entrance Motor-car on the London (Tube) Railways. (Note the glazed wind-screens, the transverse and longitudinal seats, and the steps leading to the control and driving compartments.)

electric railways usually follow the general practice for steam rolling stock, the principal exceptions being the underframes of the motor-coaches, and the provision of driving compartments in the motor and trailer coaches.

The design of the **underframe for a motor-coach** will be influenced by the type of coach, the method of control, and the disposition and weight of the control apparatus, auxiliary apparatus, &c. In multiple-unit trains the control and auxiliary apparatus may be arranged in a compartment at one end of the motor-coach (as on the London and South-Western Railway and the London tube railways), or the whole of this apparatus (with the exception of the master controller and switch panel) may be located under the coach between the bogies. As the

* See "The Design of Rolling Stock for Electric Railways" by H. E. O'Brien (*Journal of the Institution of Electrical Engineers*, p. 455).

total weight of the control apparatus for a coach equipped with four continuous-current motors may be of the order of $3\frac{1}{2}$ tons, the disposition of this apparatus must be carefully considered in the design of the underframe.

In the majority of cases the underframe is constructed of steel sections. The principal longitudinal members are of channel section, and are connected together by cross-bars and end-frames (the latter being called the "**head-stocks**") to which the buffing and draw-gear is attached. The outer longitudinal members (called the "**sole-bars**") are fitted with adjustable truss-rods,† which carry the tension component of the stress produced by the bending-moment, while the compression component of the stress is carried by the channels. The centre-pins, centre-bear-

FIG. 275.—Centre-entrance Motor-car in course of construction at the Brush Electrical Engineering Co.'s Works. View from driving end. The raised floor of the control compartment should be noted. The floor of the driving compartment is on the same level as that of the passenger compartment.

ings, and side-bearing plates are fitted to cross channels, which for a motor-coach have to be specially reinforced and braced to the sole-bars and head-stocks. In some types of underframes these channels are replaced by steel castings (called "**body bolsters**"). When the control apparatus is located in the coach-body, the sole-bars and longitudinal members are braced by diagonal bracings, but these have to be omitted when the control apparatus is fixed to the underframe. The cross-bars must then be supplemented by gusset plates.

Another type of underframe which is used for the single-phase motor-coaches on the London, Brighton, and South Coast Railway has the sole-bars in the form of plate girders, as shown in Fig. 293 (p. 348). In this

† The truss-rods are adjusted to give a slight upward deflection, or camber, to the sole-bars when the coach body is unloaded and in position on the trucks. Truss-rods are not required on steel cars in which the sides and sole-bars are designed to form plate girders.

case the control and auxiliary apparatus (which weighs approximately $6\frac{1}{2}$ tons) is supported from the underframe.

The above types of underframes are adopted for rolling stock running on suburban railways, where the dimensions do not have to conform to a restricted loading gauge. In the case of **tube railways**, however, the loading gauge is much below that of surface railways on account of the limited diameter of the tunnel. For example, in the majority of the London tube railways the internal diameter of the tunnel (for straight single track) is 11 ft. $8\frac{1}{2}$ in.,* while the height from the track rails to the top of the tunnel is 9 ft. $11\frac{1}{2}$ in. The rolling stock on these lines is of the saloon type, with end platforms and collapsible gates. The cars

FIG. 276.—Underframe of Centre-entrance Motor-car in course of construction at the Brush Electrical Engineering Co.'s Works. View from trailer end.

are built of steel,† which enables the underframe to be incorporated with the body, thereby resulting in a light construction for the underframe. As the level of the floor is only about 2 ft. above the track rails, and the wheels are 30 in. in diameter, it has been necessary to carry the sole-bars nearly on a level with the axle boxes, while the adoption

* This diameter is standard for the tubes which form part of the London Electric Railway Co.'s system (viz. the Charing Cross, Euston and Hampstead Railway; the Baker Street and Waterloo Railway; the Piccadilly and Brompton Railway). The diameters of the tunnels of the other tube railways are: 11 ft. 8 in. for the Central London Railway, 10 ft. 8 in. for the City and South London Railway (these tunnels are being enlarged to 11 ft. $8\frac{1}{2}$ in. to allow through running with the other tube railways), 16 ft. for the Great Northern and City Railway (this tube can accommodate full-size rolling stock).

† The Board of Trade require the cars operating on tube railways to be constructed of steel. Any essential woodwork must be rendered non-inflammable.

of longitudinal seats over the trucks has enabled the requisite clearance to be obtained for the radiation of the wheels.

The floor of the control compartment* of the motor-cars is raised 1 ft. 8 in. above that of the passenger compartment, in order to clear the motors and the driving wheels (which are 36 in. in diameter). Exterior and interior views of one of the motor-cars (built by the Brush Electrical Engineering Co.) on the London Electric Railway Co.'s system are shown in Figs. 273, 274,† and views of a motor-car in course of construction at the Brush Co.'s works are shown in Figs. 275, 276. These views show clearly the arrangement of the various members of the steel underframe and the body framing. It will be observed, in Fig. 273, that the side plating of the car is extended below the sole-bars (in the form of a plate girder), in order to give additional strength to the underframe at the centre-entrance doors.

TRUCKS

The trucks in use on the passenger rolling stock of railways are usually of the four-wheel bogie type with a central bolster, although in some cases (such as for dining cars, sleeping saloons, and drawing-room (Pullman) cars) a six-wheel bogie is adopted. The trucks for motor-coaches are, in general, of similar design to those for trailer coaches, except that the former are of heavier construction to withstand the greater stresses to which they are subjected. In this case, however, only four-wheel bogies are adopted, and it is general practice to equip both axles with motors. Since the curves on a railway are generally of fairly large radius, the wheel-base of the trucks can be made much greater than the values adopted on tramways; and, in practice, a wheel-base of from 6 ft. to 10 ft. is adopted, which allows the motors to be placed in the "inside" position (*i.e.* between the transoms and the axles).

Motor trucks can be divided broadly into two classes, according to the spring system adopted between the truck frame and the axles. Thus (1) the truck frame may be supported on the axle-boxes through laminated springs (see Fig. 277), or (2) the truck frame may be supported on spiral springs carried on equalising bars, the ends of which are supported directly on the boxes (see Fig. 278). In each type of truck the bolster is supported on springs carried by the spring plank, which may be of either the swinging or the rigid type, the former being the more general for railways operating at moderate speeds.

Trucks of the first class (which may be called **non-equalised trucks**) are practically standard for all British railways, while trucks of the second class (which are called **equalised trucks**) are largely used in America, and are only used to a limited extent in this country. This type of truck has superior riding qualities to the non-equalised type on poor track, but with the excellent track construction on our larger railways

* On tube railways the Board of Trade will only allow motors to be carried on the front and rear cars of a train, and no main cable may be carried through the train. Moreover, the whole of the control and auxiliary apparatus for each motor-car must be located in a steel compartment at the driving end of the car.

† The illustrations refer to the latest motor-cars in service on the Baker Street and Waterloo (tube) Railway. Motor-cars of this type have also been built by the Leeds Forge Co.

the riding qualities of the non-equalised truck are quite satisfactory. Moreover, the equalised truck is not only heavier and more costly to maintain than a non-equalised truck of equal wheel-base, but it is subjected to a tilting action during braking—the forward end of truck

FIG. 277.—Standard British Type of Non-equalised Motor Truck with motors and collector shoes (for positive and negative conductor rails) in position (Leeds Forge and B.T.-H. Co.'s.)

being depressed and the rear end raised—this action being greatest when outside hung brake shoes are used.*

In view of the large forces to which a motor truck is subjected (the truck having to perform the work of a locomotive in addition to carrying and guiding the car-body), the frame must be very rigid, and must be

FIG. 278.—Brill "27 M.C.B." Equalised Motor Truck.

sufficiently braced to maintain its "squareness" under all conditions. As the only means of bracing the side-frames is by the transoms and the end-frames, these members must be liberally designed, and must be reinforced by gusset plates at the connections to the side-frames. The

* For a full discussion of the forces produced during braking, see a paper on "Railroad Car Braking" by R. A. Parke (*Transactions of the American Institute of Electrical Engineers*, vol. 20, p. 235).

gusset plates and diagonal bracing between the side-frames, end-frames, and transoms are shown very clearly in Fig. 279, which refers to one of the motor trucks on the London, Brighton, and South Coast Railway.

The frame of a non-equalised truck may be constructed of steel plate and rolled sections, of pressed-steel plate, or of cast steel; while

FIG. 279.—Top View of L.B. and S.C. Ry. Motor Truck, showing Single-phase Motors and Brake-rigging. Note the gussets and cross bracing.

the frame of an equalised truck may be constructed of rolled sections, of forged steel, or of cast steel.

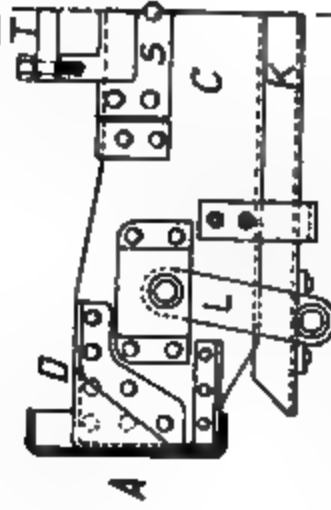
A typical non-equalised truck—which is representative of British Railway practice and is in service on a number of electric railways—is illustrated in Figs. 277, 279, 280.* The truck is built of pressed steel sections which are riveted together. The side-frames (or sole-bars) *A* (Fig. 280) and the end frames (or head-stocks) *B* are of channel section.

* The author is indebted to the Leeds Forge Co. for the drawings from which Fig. 280 was made. This figure refers to a motor-truck for the London tube railways.

FRONT ELEVATION

HALF SECTION THROUGH CENTRE

PART CROSS SECTION



DETAIL OF TRANSOM



HEADSTOCK

FIG. 280.—Fox's Pressed-steel Motor Truck. Built by the Leeds Forge Co. for the Centre-entrance Motor-cars on the London Electric (Tube) Railways.

The ends of the head-stocks and the transoms (*C*) are flanged and riveted to the side-frames, and each corner is reinforced by a gusset plate *D* in order to increase the rigidity of frame. The yokes for the axle-boxes are reinforced by "U" pieces riveted to the back of the side-frames, while the cast-steel horn-blocks (or axle-box guides) *E* are bolted to the front of the yokes. The truck frame is supported on the axle-boxes by means of the lugs *F*. These lugs rest on short volute * springs *G* which are carried on hangers *H* suspended from each end of the laminated semi-elliptic springs *J*.

The spring plank *K* (of channel section) is suspended from the transoms by swing links *L*, the upper ends of which are inclined towards the centre of the truck.† Each end of the spring plank is provided with two projections *M* which act as guides for the spiral springs supporting the bolster, similar projections being fitted to the under-side of the latter. The bolster *N* is of box section, and supports the car-body on the centre-bearing *O*,‡ the upper portion of which is fixed to the underframe, while the two portions are maintained concentric by the king pin *P*. The bolster is also fitted with side bearings *Q* which engage rubbing plates on the under-frame.§ The swing of the bolster is limited by the ends of the bolster engaging plates *R* fixed to the side frames. The centre- and side-bearings can be clearly seen in the view of the truck shown in Fig. 279.

The diameters of the wheels and axles will be influenced by the type and size of the motor. In many cases the diameter of the wheels is 36 in. The standard wheel diameter for rolling stock on steam railways is approximately 43 in. Wheels of this diameter have been adopted on most of the suburban electrifications in this country, as the trailer coaches of the electric stock can be coupled to standard steam stock.|| The diameter of the axle at the motor bearings varies from about 6 in. to 7½ in., according to the size of the motor, while the diameter at the journals varies from 4½ in. to 6 in., this dimension being influenced by the weight of the coach.

The motor is generally suspended on the nose system, the nose on the motor frame (see Fig. 18, p. 33) resting on a bracket *S* (Fig. 280) fixed to the transom. The nose is prevented from rising by the strap *T*. In some cases the nose is spring supported, the springs being carried from an angle-bar attached to the transom.

* In some cases spiral springs and concentric rubber springs are used.

† The swing links are arranged in this manner to counteract, to some extent, the centrifugal force acting on the coach when passing round curves. When the bolster swings outwards (on a curve) the inclined position of the links cause the outer portion of the coach to be raised and the inner portion to be lowered.

‡ With trucks for tube railways the centre-bearing is of the ball-bearing type, as shown in Fig. 280; but with trucks for surface railways the centre-bearing is of the spherical-seated type.

§ With coaches for surface railways the usual clearance between the side-bearings and the rubbing plates is about ½ to ¾ in. with the body of the coach central. In cases where side oscillation of the coaches cannot be tolerated (as on tube railways) the body is carried on the centre-bearing and both side-bearings, which are of the roller (or ball) type to facilitate radiation of the truck.

|| In this connection see a paper on "Electrification of Railways as affected by Traffic Considerations" by Mr. H. W. Firth (*Journal of the Institution of Electrical Engineers*, vol. 52, p. 609).

BRAKE-RIGGING

It is the general practice on railways to fit two brake shoes to each wheel for all passenger rolling stock. With motor-trucks having a wheel-base of from 6 ft. to 7 ft. there is considerable difficulty in finding room for the operating gear, since the position of the motors prevents the use of brake beams for the inner set of brake shoes. Consequently the majority of motor-trucks of this wheel-base are only provided with one brake shoe to each wheel, the shoes being arranged either in the "outside" or "inside" positions. When the wheel-base of the truck is of

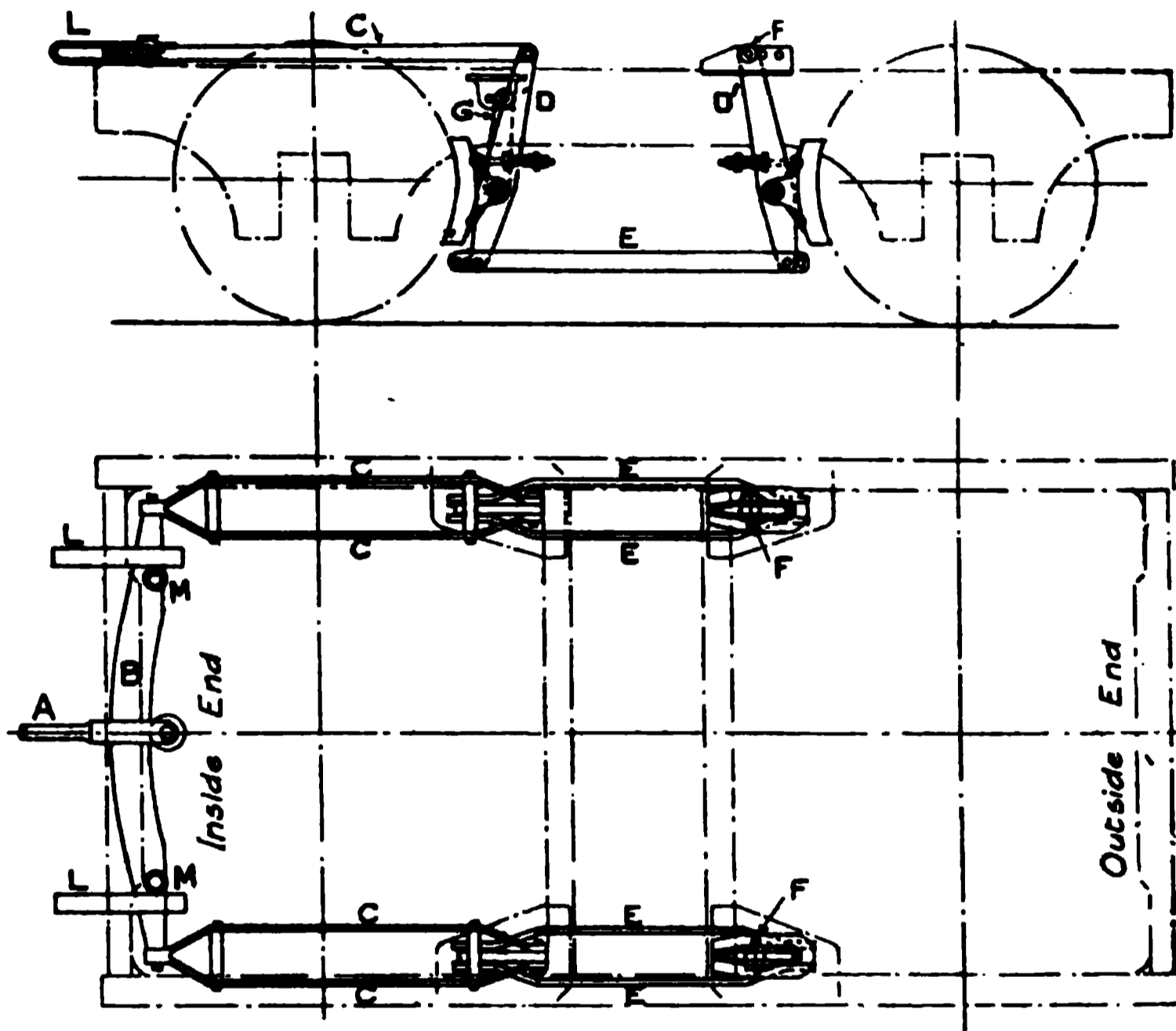


FIG. 281.—Diagram of Brake-rigging for Inside-hung Brake Shoes.

the order of 8 ft. to 10 ft., however, it is generally possible to provide two brake shoes to each wheel.*

The use of outside-hung brake shoes enables brake beams to be adopted with a convenient arrangement of levers, but these advantages result in a tilting of the truck † when the brakes are applied, the

* Examples of motor trucks fitted with two brake shoes to each wheel are in service on the following railways: The London, Brighton, and South Coast Railway (8 ft. wheel-base, see Fig. 279); The London and North-Western Railway (8 ft. 9 in. wheel-base, see *Tramway and Railway World*, vol. 37, p. 17); The London and South-Western Railway (8 ft. 9 in. wheel-base); The Lancashire and Yorkshire Railway (10 ft. wheel-base, see *Journal of the Institution of Electrical Engineers*, vol. 52, p. 452).

† The tilting action with outside and inside brake shoes is discussed fully in a paper by Mr. R. A. Parke, on "Railroad Car Braking" (*Transactions of the American Institute of Electrical Engineers*, vol. 20, p. 235).

front end of the truck being depressed and the rear end raised. This tilting action is more pronounced in trucks of the equalised type, due to the short spring-base and the method of mounting the truck frame on equaliser bars. When trucks of this type (with outside-hung brake shoes) are braked to give a high retardation, the tilting action compresses the front springs (on the equaliser bars) and removes a portion of the load from the rear springs. Thus when the car comes to rest a reaction is produced which results in a sudden backward jerk of the car-body.

The arrangement of the brake-rigging for inside-hung brake shoes is indicated in Fig. 281, which refers to the pressed-steel truck illustrated in Fig. 277. In this case it is not possible to use brake beams. Consequently the brake levers must be pivoted to the brake shoes. The force must, therefore, be transmitted in line with brake shoes, and to enable this to be done in the present case without the brake rods fouling the inner wheels, it has been necessary to adopt divided brake rods (*C*, Fig. 281). These rods are attached at one end to a radius beam *B*, and at the other end to the brake levers *D*. The latter are pivoted to the brake shoes, and the lower ends are connected to the brake levers on the outer wheels by the equalising rods *E*.

The brake shoes of the inner wheels are suspended, by links *G*, from brackets fixed to the side frames of the truck. The links *G* also support the weight of the brake levers *D* and a portion of the weight of the brake rods and equalising rods.

The brake levers *D'* (for the outer wheels) are pivoted to their respective shoes, and the upper end of each lever is provided with a fulcrum *F*, formed by angle brackets fixed to the side frames. This fulcrum is adjustable in order to allow for the wear of the brake shoes, and the effective length of the equalising rods is adjustable for the same reason.

The radius beam *B* is usually supported by guides *L* attached to

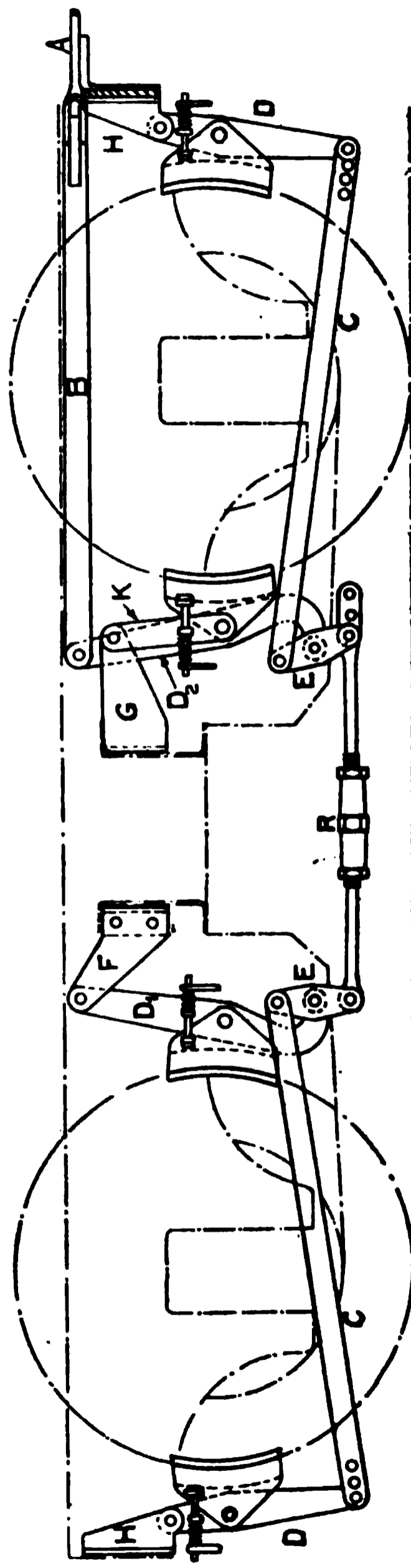


FIG. 282.—Diagram of Brake-rigging for Two Brake Shoes (without Brake-beams) to each Wheel.

the inner headstock (see Fig. 280), and the transverse movement of the beam is limited by the rollers *M* engaging with these guides. The radius beam and guides can also be seen in Fig. 279.

When a tension is applied to the pull-rod *A*, the brake shoes of the inner wheels come into operation first, and the thrust is then transmitted through the equalising rods to the brake shoes on the outer wheels.

In Fig. 282 is given a diagram of the arrangement of brake-rigging for a motor truck with two brake shoes to each wheel. The outside brake shoes for both wheels are pivoted to the brake levers *D*, which are suspended from brackets *H* on the headstocks of the trucks. The brake levers *D*₁ of the inside shoes of the outer wheels are suspended in a similar manner from brackets *F*, fixed to the transom, but for the inner wheels of the trucks the inside brake shoes (and the brake levers *D*₂ connected to them) are suspended, from brackets *G* fixed to the opposite transom, by the links *K*. The inside brake levers *D*₁, *D*₂ are of a special "L" shape, and their lower ends are connected to the lower ends of the outside brake levers *D* through the equalising levers *E* and the brake rods *C*, the other (lower) ends of the equalising levers being connected together by the adjustable rod *R*. The upper ends of the inside brake levers *D*₂ (for the inner wheels of the truck) are connected to a radius beam *B* by divided brake rods, and the radius beam is operated by the pull rod *A* as explained above.

When the brakes are applied the action is as follows:—The inside shoes of the inner wheels come into operation first, and provide the brake levers *D*₂ with fulcrums. The thrust is then transmitted to the other brake shoes by means of the equalising levers and brake rods.

EXAMPLES OF MOTOR-COACHES

The general design of motor-coaches operating on the electrified lines of the larger steam railways in this country is, in many cases, similar to that of the standard rolling stock in use on those railways. In some cases (*e.g.* the London and South-Western Railway and the Metropolitan Railway) the steam trailer stock has been reconstructed as motor-coach electric stock. In this reconstructed stock the control and auxiliary apparatus is located in the motorman's compartment (which adjoins the luggage compartment), so that the reconstruction of the underframe of the coach has been avoided. Of course the existing underframe has had to be strengthened at some places, and new trucks have had to be provided.

In other cases of railway electrification entirely new rolling stock has been provided. With the provision of new stock and multiple-unit control, the control and auxiliary apparatus may be located under the coach body, so that only the master controller and the control circuit switches are required at the driving platform, which, with the saloon type of coach, may form part of the vestibule. This arrangement of the apparatus is convenient for urban railways—such as the London Underground Railways—on which a considerable variation of the composition of the trains is required throughout the day.

A view of a **standard steel motor-coach of the District Railway** (London Underground Railways) is given in Fig. 283. The coach is

FIG. 283.—Standard Steel Motor-coach of the District Railway, London.

of the saloon type, with centre and end sliding doors. The underframe is of the trussed type, and is mounted on two bogie trucks, of which one is equipped with motors. The control and auxiliary apparatus is fixed to the underside of the underframe, and the boxes containing the con-

FIG. 294.—Interior of District Railway Steel Motor-coach.

tactors, reverser, and circuit-breaker can be seen in the illustration. Each truck is equipped with positive and negative collector shoes, and all collector shoes of like polarity are connected in parallel by means of "bus-line" cables. The continuity of these cables is maintained by means of couplers and jumper cables, a typical coupler and socket

being shown in Fig. 285. The sockets for the bus-line and control-circuit cables are duplicated at each end of the coach, so that it is unnecessary to cross the jumper cables in the event of a coach being turned round when making up the train.

An interior view of the coach, showing the glazed wind-screens, the steel framing for the seats, and the arrangement of the lighting, is given in Fig. 284, while the principal dimensions and other data are given in Table XII.

The general features of the all-steel motor cars on the London (tube) railways have already been described. In these cars the whole of the control and auxiliary apparatus is located in a steel compartment at the driving end of the car, removable louvred shutters being provided for the purposes of ventilation and inspection of the apparatus (see Fig. 273). The compartment is also provided with a switch-panel, on which are mounted the switches for controlling the motor control, and auxiliary

FIG. 285.—B.T.-H. Bus-line Coupler-plug and Socket.

circuits. Views of a typical panel are given in Fig. 286. The apparatus mounted on the upper portion of the panel comprises:—A single-pole, quick-break, lever switch for isolating the main circuit of the car, a trolley-plug socket,* cartridge fuses for voltmeter and auxiliary circuits, and an enclosed switch, with magnetic blow-out, connected between the trolley-plug socket and the motor circuit. The lower portion of the panel is equipped with a control switch, with "set" and "trip" positions, for the automatic circuit-breaker; three enclosed switches with magnetic blow-out and cartridge fuses for the control, lighting, and compressor-motor circuits; the automatic accelerating relay; cut-out switch, with fuses, for the control circuit of the motor-car; cut-out switch for train (control) cable; connection box. Data of these cars are given in Table XII.

In the motor-coaches of the Lancashire and Yorkshire Railway (Liverpool-Southport section) the main controller and protective apparatus are located in a steel compartment (which also forms the luggage compartment), while the rheostats and motor-driven exhausters are located under the coach body. The majority of the coaches are provided with direct control, but a number are arranged for multiple-unit control.

* The car sheds are equipped with overhead trolley wires instead of conductor rails, and current is supplied to the train by means of an over-running trolley and a flexible cable which is plugged into the socket on the switch-panel.

A special feature in the equipment is the use of the vacuum brake and the incorporation of the "dead-man's handle" with the brake-operating handle instead of the controller handle.

Views of the driving compartments for direct control and multiple-

Covers removed.
Covers on.
FIG. 286.—B.T.-H. Switch-panel for Motor-cars operating on Tube Railways. [The panel is equipped with switches for controlling all the circuits on the train.]

unit control are given in Figs. 287, 288. The motors on the forward and rear motor-coaches of a train are supplied through circuit-breakers at the driving end (see connections, Fig. 141, p. 168), and these circuit-breakers are fitted with shunt-tripping coils in addition to the overload tripping coils. The shunt-tripping coils are energised when the operating

Multiple-unit Control.

Direct Control.

Handle for horn.

Main ammeter.

Main switch.

*Main circuit-
breakers.*

*Emergency tripping
coils for circuit-
breaker.*

Master controller.

Motor cut-out switch.

Contactors.

Vacuum brake.

Hand brake.

*Emergency tripping
coil for vacuum
brake.*

*Switch for exhaust
motor.*

Main circuit-breaker.

*Fuses for exhaust
motor and brake
circuits.*

*Emergency tripping
coil for circuit-
breaker.*

Controller.

*Emergency handle,
vacuum brake.*

*Vacuum brake oper-
ating valve.*

Main switch.

*Emergency tripping
coil for vacuum
brake.*

Figs. 287, 288.—Driving Compartments of L. and Y. Ry. (Liverpool-Southport Section) Motor-coaches.

handle of the brake valve is released by the driver. The release of the operating handle of the brake valve also energises an electro-magnetic valve, which breaks the vacuum and thereby applies the brakes. Data of these motor-coaches are given in Table XII.

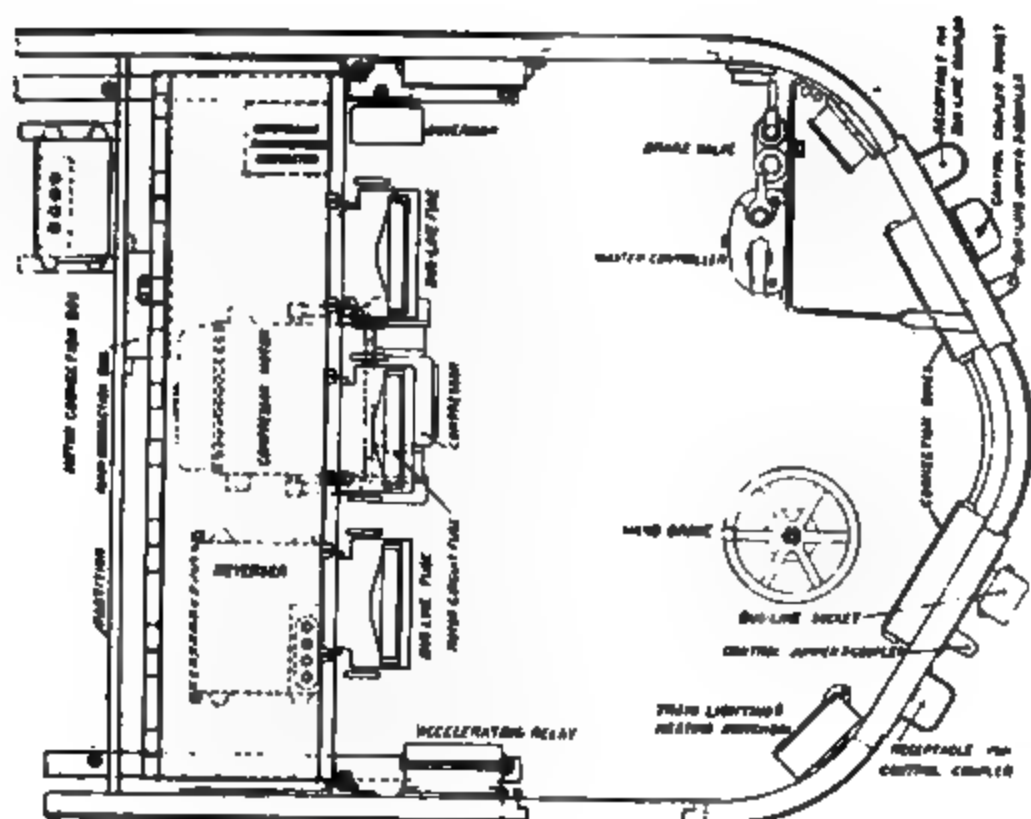


FIG. 289.—Elevation and Plan of the Control (and Driving) Compartment of a Motor-coach on the London and South-Western Railway.

The motor-coaches in service on the London and South-Western Railway and the London and North-Western Railway are also provided with separate compartments for the control apparatus. In the case London and South-Western Railway, the old steam rolling

stock (compartment type) has been reconstructed with a control compartment (which adjoins the guard's compartment) at one end of each

**FIG. 289a.—View of the Control and Auxiliary Apparatus in
L. and S.W.Ry. Motor-coach.**

FIG. 290.—L. and S.W.Ry. Three-coach Electric Train.

motor-coach. The whole of the control and auxiliary apparatus (including the rheostats) is located in this compartment, and the disposition of

the apparatus is shown in Figs. 289, 289a. It will be observed, from Fig. 289, that the end of the coach is of special parabolic shape to reduce the head resistance (see Chapter XVIII). The motor-coaches are each equipped with two 275-H.P. motors, and are arranged for multiple-

FIG. 29L.—Driving Compartment of L. B. and S. C. Ry. Motor-coach. **NOTE.**—The covers have been removed from the master controller and compressor-motor governor.

unit control. A view of a "train unit," consisting of two motor-coaches and one trailer-coach, is shown in Fig. 290, and data of the motor-coaches are given in Table XII.

With single-phase motor-coaches provision must be made for housing all the high-tension apparatus in a steel compartment separate

from the low-tension, control, and protective apparatus. An excellent example of the arrangement of the high-tension, low-tension, and control apparatus is found in the single-phase motor-coaches of the **London, Brighton, and South Coast Railway**. The high-tension and low-tension

FIG. 292.—High-tension (left) and Low-tension (right) Compartments on
L.B. and S.C.Ry. Motor-coach.

apparatus are located in separate chambers in the motorman's compartment (which also forms the luggage compartment), while the main transformer, air compressor, contactors, and reverser are located under the coach body (see Fig. 186, p. 217). Views of the driving compartment and the high- and low-tension chambers are shown in Figs. 291, 292, while in Fig. 293 is shown a view under a coach (with the trucks

removed) in which the main transformers, the contactor boxes, the air brake reservoir, and details of the wiring and the underframe can be seen.

The **high-tension chamber** is shown to the left in Fig. 292. At the lower portion of the chamber we have the auxiliary transformer and the main fuses (in the primary circuit of each main transformer). Above these fuses we have the electrically-operated main oil-switch, and at the upper part of the chamber we have the earthing switch, choking coil, and fuses for the auxiliary transformer. The door of this chamber is mechanically interlocked with the collector bows (by the levers shown in the roof), so that the door cannot be opened if either bow is raised,

FIG. 293.—View underneath L.B. and S.C.Ry. Motor-coach, with trucks removed, showing the location of control apparatus and wiring. *A*, body bolster; *B*, side bearing; *C*, contactor box; *D*, reverser box; *E*, centre bearing; *F*, cross-bar; *S*, plate-girder sole-bars; *R*, main reservoir; *T*, main transformer.

while the opening of the door closes the earthing switch which earths all the high-tension wiring.

In the **low-tension chamber** (shown to the right in Fig. 292) are located the control circuit cut-out switches, fuses, and connection boxes.

The motor-coaches are of the compartment type, and have plate-girder underframes, as shown in Fig. 293. A view of a six-coach train, consisting of two motor-coaches and four trailer-coaches, is shown in Fig. 448 (p. 548). The equipment of each motor-coach comprises four 150-H.P. compensated-repulsion motors, two main transformers, two reversers and contactor groups (one group for each pair of motors), an electrically-driven air-compressor, collector bows, and the apparatus (described above) located in the high- and low-tension chambers. The motors are controlled on the multiple-unit system, as described in Chapter V. Data of these motor-coaches are given in Table XII.

TABLE XII
DATA OF MOTOR-COACHES

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.
Type of coach	Saloon	Saloon	Saloon	Saloon	Saloon	Saloon	Saloon	Saloon	Compartment	Compartment	Saloon
Length of coach	60' 5"	63' 0"	63' 7"	49' 9"	51' 10"	51' 10"	45' 6"	50' 0"	52' 8"	58' 0"	60' 0"
Width of coach	9' 10½"	9' 10½"	9' 10½"	8' 8"	8' 9"	8' 9"	8' 6"	8' 9"	8' 0"	8' 0"	9' 0"
Seating accommodation	60	80	80	48	48	48	42	36	60	70	72
Distance between bogie centres	40' 6"	40' 6"	45' 0"	34' 1"	35' 0"	35' 0"	29' 0"	33' 11"	35' 10½"	35' 0"	42' 0"
Wheel-base *	8' 0"	8' 0"	10' 0"	7' 3"	7' 0"	7' 0"	6' 0"	5' 0"	8' 9"	8' 0"	8' 6"
Diameter of wheels *(in.)	42	42	44	36	38	36	35	36	42½	43½	43½
Gear ratio	1.95	1.95	2.48	3.37	3.5	3.5	3.94	3.37	2.81	4.28	2.93
Number of motors per coach	4	4	4	2	4	4	2	2	2	4	2
Rated H.P. of each motor	150	150	250	230	230	180	125	230	275	150	180
Weight of bogie truck without motors * (tons)	4.85	6.5	8.85	6.0	6.56	5.4	3.9	4.35	8.25	7.5	7.0
Weight of motors with gear and gear case (tons)	2.92	2.84	4.12	2.72	2.72	2.3	1.96	2.78	3.5	2.85	2.9
Weight of truck with motors and brake gear (tons)	11.0	12.5	17.85	11.44	12.0	9.8	7.8	9.9	14.75	12.96	12.8
Weight of complete electrical equipment, not including auxiliary apparatus for brakes (tons)	14.68	14.33	23.67	7.3	18	14	5	7.8	9.75	18.85	14.5
Weight of car-body complete with all equipment (tons)	24	25.45	31.7	18.2	20.0	20.7	13.3	14.65	16.95	23.9	22.7
Weight of coach completely equipped (tons)	46	50.5	67	33	44	40.3	23	27.5	36.2	51.5	40
System of Control	Direct	←	Multiple Unit	→							

* Upper figures refer to motor truck, lower figures refer to trail truck. Reference : I., II., III. Lancashire and Yorkshire Ry. (Liverpool-Southport section) ; IV. District Ry. (steel coaches) ; V. Metropolitan Ry. (London) ; VI. Great Western Ry. (London Suburban) ; VII. Central London Ry. (wooden coaches) ; VIII. London Electric (tube) Railways (steel cars) ; IX. London and South-Western Ry. ; X. London, Brighton, and South Coast Ry. ; XI. Midland Ry. (Heysham-Morecambe branch).

BRAKES

The brakes on railway passenger rolling stock are always operated by power, since it would be impossible to obtain sufficient braking force with hand-operated brakes. Hand brakes, however, are fitted to motor-coaches and guards' compartments for operation by the motorman or guard in cases of emergency.

Two types of power brakes have been developed, viz. the compressed air (or Westinghouse) brake, and the vacuum brake. The former brake is largely used on electric railways, and is also extensively adopted in America on steam railways; while the vacuum brake is standard on all our large steam railways, and has been adopted on the electrified lines of the Lancashire and Yorkshire Railway.

For electric railways the compressed-air brake possesses some advantages over the vacuum brake, as compressed air can be stored so that a quick release of the brakes can be obtained; whereas, with the vacuum brake, the vacuum must be created by means of a pump or exhauster. This disadvantage, however, can be overcome by the use of vacuum reservoirs and equalising valves (as used on the Lancashire and Yorkshire Railway), by which means the brakes can be released with sufficient rapidity to enable 10-second stops to be adopted.

The vacuum brake.—In its simplest form this brake consists of a vertical cylinder (called the brake-cylinder) fitted with a piston and piston-rod, the latter operating the brake-rigging through suitable levers. A vacuum is maintained continuously on the top of the piston, while air—at atmospheric pressure—can be admitted to, or exhausted from, the underside of the piston. Under normal conditions (*i.e.* brakes off) a vacuum is maintained on both sides of the piston, and the latter rests against the lower cylinder cover. When an application of the brakes is required, the vacuum is broken on the underside of the piston and the latter is forced upwards, thereby applying the brakes. The brakes are released either by re-creating the vacuum, or by equalising the pressure on each side of the piston.

In practice each coach is equipped with one or two brake-cylinders (according to the nature of the brake-rigging on the bogies) which are connected to the "train-pipe," as shown in Fig. 294. The latter is continuous throughout the train, and is connected to the operating (or driver's) valve on the locomotive or motor-coach. On steam trains this valve is a combination of an air valve and two steam ejectors, one large and one small. Under normal conditions the small ejector maintains the vacuum in the train-pipe, while the large ejector is only operated for releasing the brakes. On electric trains these ejectors are replaced by a motor-driven exhauster (or vacuum pump) which is run at two speeds—one being double the other—the higher speed being only used for releasing the brakes. With continuous-current equipments the lower speed is obtained by inserting a rheostat in series with the motor, and the rheostat is cut out when the driver's valve is moved to the "off" or "release" position. With single-phase, alternating-current equipments two or more operating speeds for the exhauster motor can readily be obtained from tappings on the auxiliary transformer (see Figs. 201, 202).

One type of vertical brake cylinder (manufactured by the Vacuum Brake Co.) is shown in Fig. 294. The cylinder *A* is combined with the vacuum chamber *B*, which is provided with trunnions for mounting in a vertical position under the coach. The piston *C* is an easy fit in the cylinder, and is provided with a rolling rubber ring *D*, while the piston-rod *E* is provided with a packing gland in the lower cylinder cover. The sides of the piston near the top are provided with three small holes and ball valves (one of which is shown at *F*), by means of which communication can be established between the vacuum chamber and the underside of the piston when the pressure in the former exceeds that in the lower portion of the cylinder.

This portion of the cylinder may be connected directly to the train-pipe, or the connection may be made through an automatic valve as described below. The vacuum chamber can also be connected to the train-pipe through the release valve *G*, which is normally held on its seat by atmospheric pressure acting on a diaphragm.

When the brake is "off" the vacuum is maintained in the train-pipe, vacuum chamber, and on the underside of the piston, and any air which finds its way into the vacuum cylinder is exhausted through the ball valves. When an application of the brakes is required, the train-pipe is opened to the atmosphere, and air is admitted to the underside of the piston, which is moved upwards. The force with which the brake shoes are applied to the

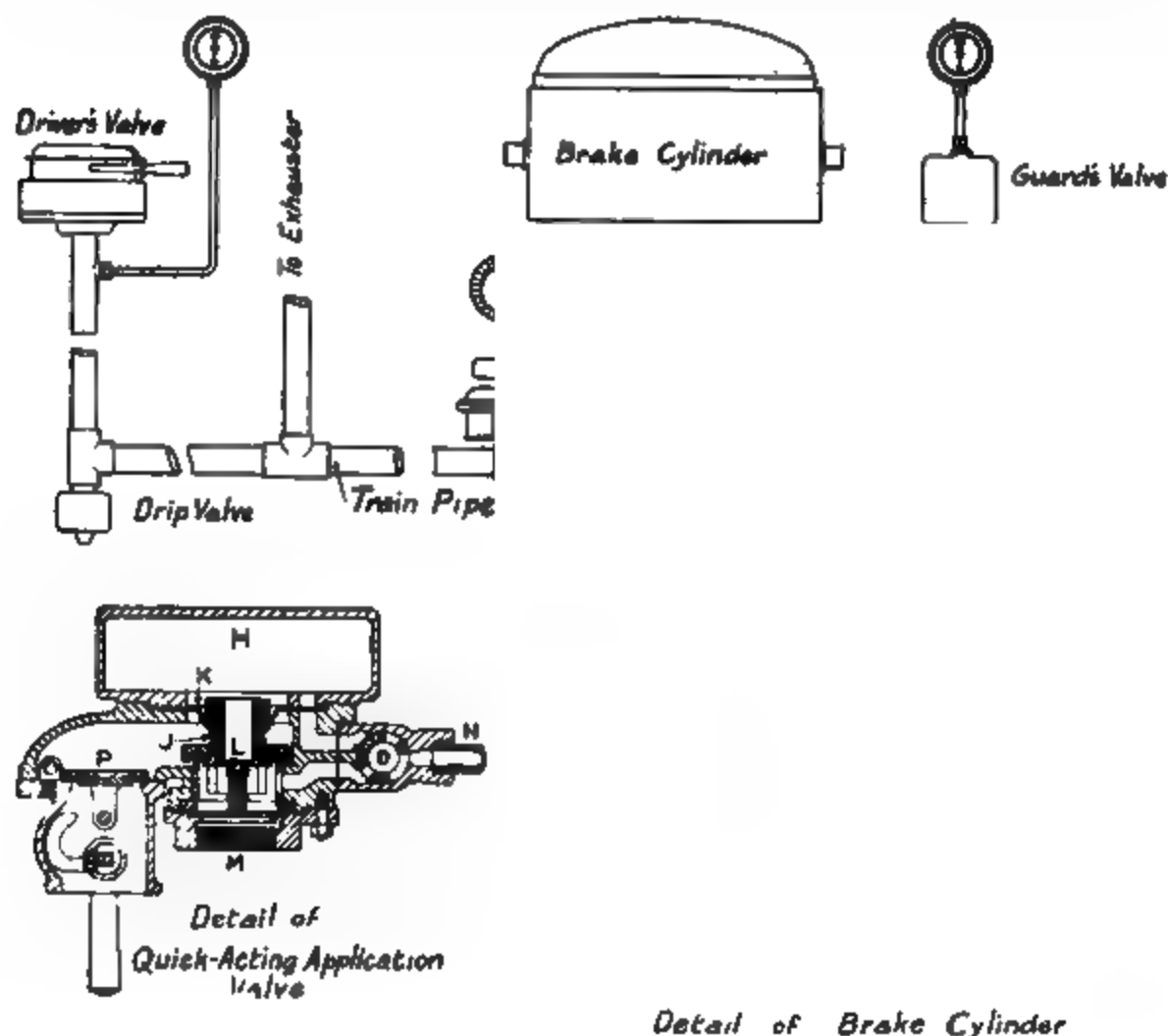


FIG. 294.—General Arrangement of Essential Parts of Vacuum Brake (Vacuum Brake Co.).

wheels depends on the rapidity with which the vacuum is destroyed, while the brakes may be partially released by partially restoring the vacuum.

The air in the train-pipe is prevented from reaching the vacuum chamber (and the top of the piston) by the ball valves and the packing ring. The function of the release valve is to allow the brakes to be released on a coach which is disconnected from the locomotive. This is done by lifting the valve from its seat, which equalises the pressure on both sides of the piston, thereby allowing the latter to return to the bottom of the cylinder.

When a quick-acting brake is required on a long train, the brake cylinders are not connected directly to the train-pipe but to auxiliary valves which are connected to the train-pipe and to the atmosphere. A cross-section of one type of auxiliary valve (called a "quick-acting application valve") is shown in Fig. 294. A rubber-seated valve *J* is provided with a diaphragm *K*, over which

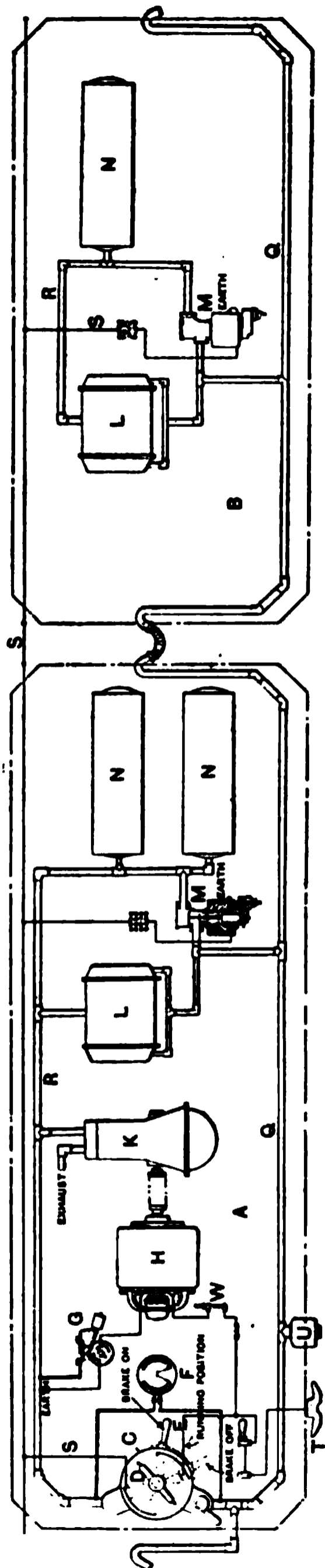


FIG. 295.—General Arrangement of Vacuum-brake Apparatus on Lancashire and Yorkshire Railway's Motor-coach Trains.

is placed a small air-chamber *H*. This air-chamber communicates with the train-pipe through a small annular space formed by the fixed stem *L* and a central hole in the body of the valve *J*. The underside of the diaphragm and the top of the valve *J* can be placed in communication with the atmosphere by means of the hinged clap-valve *P*. Under normal conditions valve *J* is maintained on its seat by the excess of pressure on the upper part of the valve, the underside of the latter and the top of the diaphragm being connected to the train-pipe (at *M*). When an application of the brake is required, the vacuum in the train-pipe is destroyed by operating the driver's valve. This unseats the valves *J* and *P*, and air is admitted through the latter to the train-pipe and brake cylinder, thereby producing a rapid application of the brakes throughout the train.

The brake cylinder in service on the electrified lines of the **Lancashire and Yorkshire Railway** differs in several features from that described above. For instance, the cylinder is mounted horizontally, and is provided with two double-acting pistons (from which the brake-rigging on each truck is operated), while the cylinder is used in conjunction with vacuum reservoirs and electrically-operated equalising valves. The general arrangement of the brake apparatus for a two-coach train (consisting of one motor-coach and one trailer-coach) is shown diagrammatically in Fig. 295. In this diagram the brake cylinders are shown at *L*, the vacuum reservoirs at *N*, the equalising valve at *M*, and the train-pipe at *Q*. The motor-coach *A* is shown equipped with an electrically-driven exhaustor *H*, *K* (with a governor *G*,* and a controlling switch *W*); a driver's valve *C*; a vacuum gauge *F*; a drip-valve *U*, for the train-pipe; and a collector shoe *T*. The driver's valve *C*, in addition to the usual valve and ports, is fitted with a switch *D*, by means of which the brake-control cable *S* (to which the solenoids of the equalising valves are connected) is energised when the handle *E* is moved to the "off" position.

In the "running" position of the handle the exhaustor maintains a vacuum in the reservoirs, the train-pipe, and in each portion of the brake cylinders, the pistons being maintained at the ends of the cylinders by springs.

* The governor controls the motor driving the exhaustor in a manner similar to that used in connection with motor-driven air compressors. The motor is stopped when the vacuum reaches 20 in., and is started when the vacuum falls to 15 in.

[NOTE.—The equalising valves are fitted with ball valves, so that the reservoirs on the trailer-coaches can be exhausted through the train-pipe. In the normal position of the equalising valves, communication is cut off between the vacuum reservoirs and the ends of the brake cylinders.]

When the driver's valve is moved to the "brake on" position, the train-pipe is connected to atmosphere, and the pistons in the brake cylinders move inwards, thereby applying the brakes. When the driver's valve is moved to the "brake off" position, the train-pipe is connected to the exhaustor, and, at the same time, the equalising valves are operated, so that communication is established between the centre and the ends of each brake cylinder. The pressure on each side of the pistons is, therefore, equalised, and the pistons return to the ends of the cylinder (thereby releasing the brakes) under the action of the springs. When the handle is returned to the "running" position,

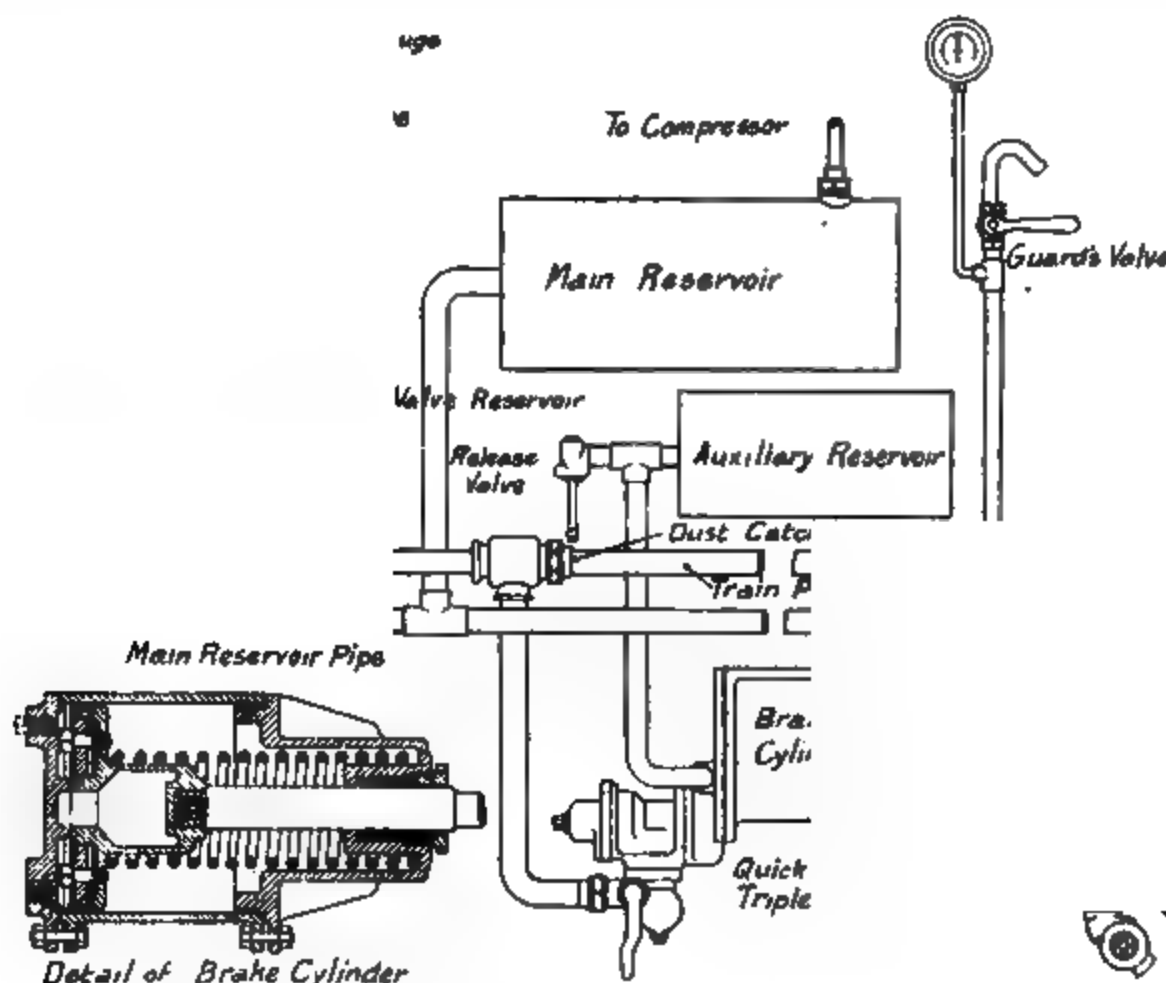


FIG. 296.—General arrangement of essential parts of Westinghouse Quick-acting Compressed-air Brake (Westinghouse Brake Co.).

position, the equalising valves resume their normal position, and the vacuum is re-established through the train-pipe.

The equalising valves are fitted with a device for operating the valves by hand, so that the brakes can be released on an isolated coach.

The Compressed-air Brake.—In its simplest form the compressed-air brake consists of a reservoir (in which compressed air is stored), a brake cylinder, an operating valve, and a train-pipe. The brake cylinder is of the single-acting type, and is shown in Fig. 296.

The brakes are kept "off" by springs in the brake cylinders acting against the pistons, while they are applied by admitting compressed air, from the reservoir, to the back of the pistons, the force of the application depending upon the quantity of air admitted to the brake cylinders. The brakes are released by exhausting the air from the brake cylinders, which is accomplished by means of the operating valve.

When this brake is used on trains consisting of several coaches, additional features are required, and we shall now confine our attention to the latest type of the brake, which is known as the **quick-acting** type.

A diagram of the essential parts of this type of brake is shown in Fig. 296. Each coach is equipped with a brake cylinder, an auxiliary reservoir, a "triple valve," and a "train pipe" (to which the triple valve is connected); while the motor coaches are equipped, in addition, with a compressor, a main reservoir, and the operating (or driver's) valve.

The train-pipe is continuous throughout the train, and is connected to the driver's valve, to which is also connected a pipe from the main reservoir, and a connection to the atmosphere.

The main-reservoir pipe is also continuous throughout the train, and it connects the main reservoirs to the compressors. Each coach of a motor-coach train must, therefore, be provided with two hose couplings at each end (see Figs. 283, 290).

The driver's valve is of the rotary type, and can connect (1) the train-pipe to the main reservoir, (2) the train-pipe to atmosphere, while it can also cut off the connection between the train-pipe, the main reservoir, and atmosphere.

The function of the triple valve is to admit air from the auxiliary reservoir to the brake cylinder, this operation depending upon the *difference* of pressure between the auxiliary reservoir and the train-pipe. When the pressure in the auxiliary reservoir exceeds that in the train-pipe (such as would happen if the driver's valve connected the latter to atmosphere) the triple valve admits air to the brake cylinder and the brakes are applied. On restoring the pressure in the train-pipe (e.g. by connecting it to the main reservoir), the triple valve releases the air in the brake cylinder and charges the auxiliary reservoir.

In order to secure a quick release after an application of the brakes, the pressure in the auxiliary reservoirs is about 20 lb. per sq. in. lower than the pressure in the main reservoir (which is between 80 and 90 lb. per sq. in.). With normal applications of the brake it is necessary to discharge the air gradually from the train-pipe and to stop the exhaust gently. This is accomplished by means of an equalising piston in the driver's valve, in conjunction with a small reservoir (called the equalising or brake-valve reservoir). The equalising piston controls the exhaust valve (in the driver's valve) for the train-pipe, and is operated by the difference of pressure between the brake-valve reservoir and the train-pipe. The driver's valve is constructed so that for *normal applications* of the brake, the air is exhausted from the brake-valve reservoir, and by means of the equalising piston a corresponding reduction of pressure is obtained in the train-pipe.

The *gradual* reduction of pressure in the train-pipe causes the triple valves to admit air gradually from the auxiliary reservoirs to the brake cylinders, so that the brakes are applied gradually throughout the train.

When a *rapid application* of the brakes is required in cases of emergency, the driver's valve is arranged to exhaust air directly from the train-pipe, thereby producing a *sudden* reduction of pressure. Under these conditions the triple valves admit air from *both* the train-pipe (through a check valve) and the auxiliary reservoirs to the brake cylinders, so that a rapid application of the brakes occurs throughout the train.

With the above forms of the compressed-air brake a reduction in the braking effort (after the brakes have been applied) can only be obtained by *fully releasing* the brakes and re-applying them. This disadvantage has recently been overcome by the introduction of a **variable release device**,* by means of which the release of the air from the brake cylinders is under control, so that the brakes can be *partially* released.

* For details of the variable release air brake, see *The Electric Journal*, vol. 10, p. 130, article on "The Electro-Pneumatic Brake System."

CHAPTER XVII

ELECTRIC LOCOMOTIVES

IN Chapters II and III we have shown, from dynamical considerations, that the requirements for the successful operation of urban and suburban traffic are quite different from those for main-line traffic. Thus in suburban traffic the energy consumption is considerably influenced by the acceleration, the retardation, and the weight of the train, while in main-line traffic these quantities have only a slight influence on the energy consumption. Therefore the suburban train must be of relatively light weight, with the non-passenger-carrying portion restricted to a minimum. These conditions are satisfied by excluding the locomotive from the train and equipping the coaches with motors, so that the whole or a portion of the weight of the passengers and rolling stock is utilised for adhesion.

On the other hand, the requirements of long-distance main-line traffic involve high operating speeds and the running of various types of rolling stock, such as restaurant and dining cars, sleeping saloons, corridor and non-corridor coaches, brake vans, &c. Under these circumstances the use of motor-coach trains would involve several difficulties in operation, while the maintenance costs would be prohibitive. Therefore this class of traffic must be handled by locomotives.

On a large railway system there will be two other classes of traffic to be catered for, viz. (1) local passenger traffic, intermediate between suburban and long-distance traffic; (2) freight or goods traffic. The latter class of traffic, obviously, must be operated by locomotives, and a consideration of the operating conditions for local passenger traffic will generally show that locomotive operation is desirable in this case.

Now, as the services for which locomotives are required differ considerably from one another, it is apparent that the locomotives for operating these services will differ from one another in mechanical design and electrical equipment, so that a locomotive designed for one class of traffic will generally be unsuitable for handling another class of traffic. This point must be carefully considered when locomotives of different designs are compared.

The features external to a locomotive which have to be considered in its design include (a) those associated with the permanent-way, such as (1) the loading gauge, (2) the maximum concentrated weight which can be carried by the permanent-way; (b) those associated with the rolling stock, as for example, (3) the strength of the couplings and draw-gear; and (c) those associated with the service requirements, which

comprise (4) the tractive-effort or draw-bar pull required, and (5) the speed at which this pull must be exerted. In addition, the influence of the wheel arrangement and the disposition of the various parts of the locomotive must be considered with reference to the wear of the permanent-way and the cost of maintenance.

With electric locomotives the loading gauge will affect the height of the roof of the cab when bow or pantagraph collectors are used, since the lowest operating position of the latter must be within the loading gauge. At the present time, however, the loading gauge (of standard-gauge railways) has not introduced any serious limitations with electric locomotives.

The **maximum load** which can be placed on a pair of driving wheels depends on the strength of the permanent-way, and is limited to about 20 tons, while the strength of bridges will generally not allow this load to be carried on more than three axles having an overall wheel-base of 14 ft.*

The **maximum draw-bar pull** which the locomotive must exert is limited by the strength of the couplings and draw-gear. With the passenger rolling stock in use on our main-line railways the draw-bar pull at starting must be limited to about 16 tons. With wagons and vans for goods and mineral traffic the draw-bar pull must be limited to about 12 to 14 tons, on account of the large number of privately-owned wagons in use.† When specially-built wagons can be adopted, the limiting value of the draw-bar pull can be raised to about 30 tons. In a given case the draw-bar pull required can be estimated when the weight of the train, the acceleration, the gradient, and the train resistance are known; while the tractive-effort at the driving wheels will be obtained by adding the resistance of the locomotive ‡ to the draw-bar pull. In calculations for electric trains it is customary to include the resistance of the locomotive with the train resistance, as the performance curves of the locomotive are expressed in terms of the input to the motors. On the other hand, with steam trains the tractive force is always measured at the draw-bar, and the performance curves of the locomotive are expressed in terms of this quantity.

In order that the locomotive shall be capable of exerting the required tractive-effort, it is necessary that sufficient weight be placed on the driving wheels to prevent slipping. The total weight on the driving wheels is usually called the "**adhesive weight**," and its value is decided from considerations of the coefficient of friction between the wheels and rails. The ratio of the tractive-effort to slip the wheels and the adhesive weight is called the "**coefficient of adhesion**," the value of which is influenced by the condition of the rails and also by the speed.§ Under normal starting conditions, with clean dry rails, it is customary to assume a value of 0·25 for the coefficient, and a maximum value of 0·3 when sand is used. If the rails are wet or greasy, the coefficient of adhesion will be much lower; thus, for a thoroughly wet rail a value

* This corresponds to a modern 4-6-0 steam locomotive in which the adhesive weight is about 60 tons.

† The usual type of coupling on wagons is tested to 50 tons, and a factor of safety of 4 is usually allowed.

‡ The resistance of locomotives is given in Chapter XVIII, p. 423.

§ Average values of the coefficient of adhesion at various speeds are:—

Speed ml.p.h.	0	10	20	30	40	60
Coefficient of adhesion	0·25	0·18	0·14	0·12	0·1	0·09

of 0.18 to 0.2 is usually assumed, while for a moist or greasy rail the coefficient is of the order of 0.15. The application of sand, however, will enable these values to be increased to about 0.25. If the tractive-effort fluctuates during starting, the maximum value of the tractive-effort must not exceed (adhesive weight \times coefficient of adhesion). Hence the more uniform the tractive-effort during the starting and initial accelerating periods the heavier will be the train which can be operated by a locomotive of given adhesive weight. This point is of considerable importance for goods traffic, where the weight of the train

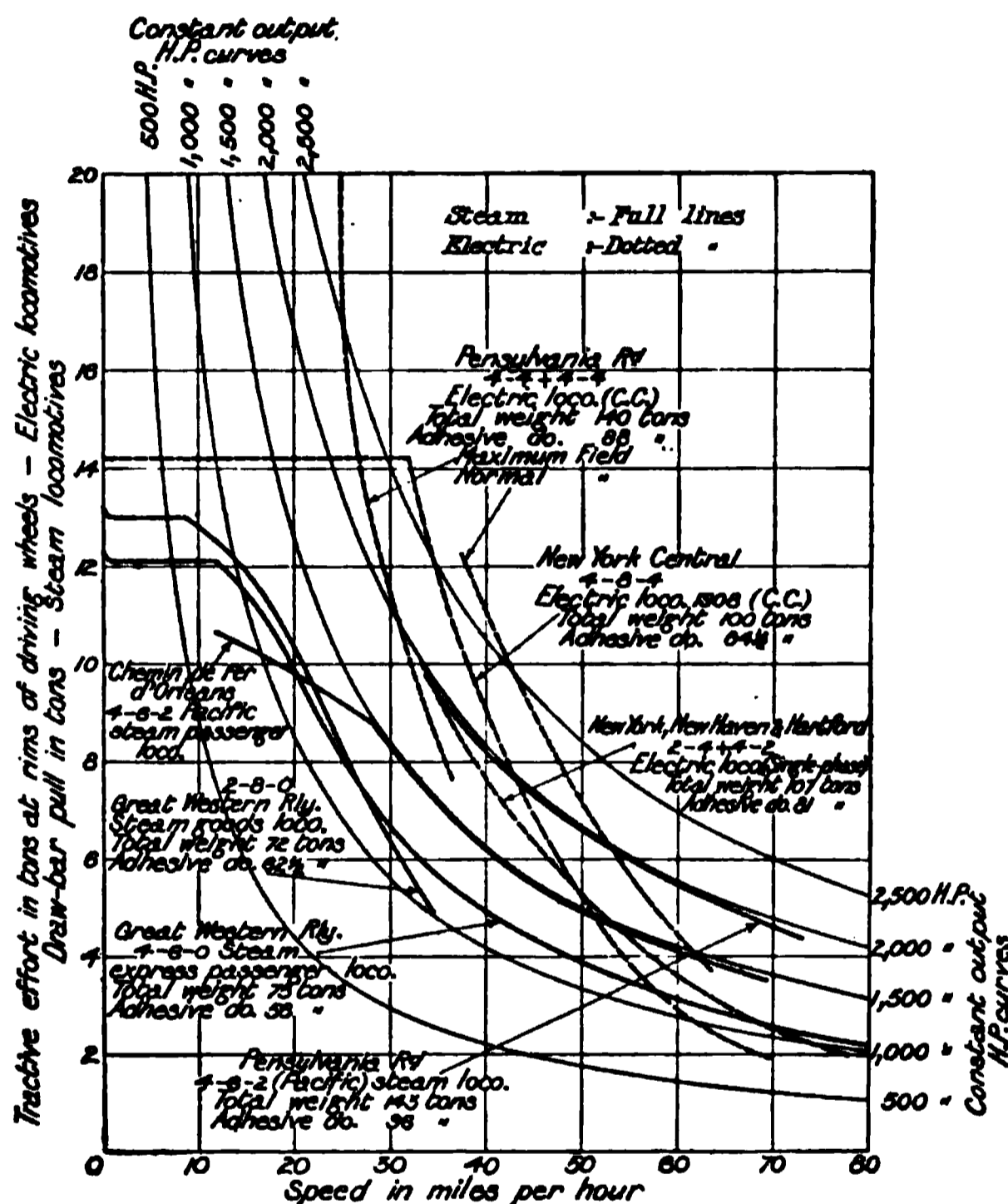


FIG. 297.—Dynamical Performance Curves of Steam and Electric Locomotives.

usually approaches the maximum weight which can be handled by the locomotive.

Since all locomotives have a limiting maximum tractive-effort, which is determined from considerations of the adhesive weight and coefficient of adhesion, it is desirable, in electric locomotives, that the motors should be able to exert this tractive-effort without damage to themselves or to the control gear. The adhesive weight must therefore be such that the maximum tractive-effort (corresponding to a coefficient of adhesion of 0.25) does not overload the motors more than 75 per cent.

Characteristic Features of Electric Locomotives.—In all electric motors operating at a constant voltage, the speed and torque are intimately associated with each other. Hence under these conditions a

variation of, say, the tractive-effort will produce a corresponding variation of the speed, and when series motors are used the tractive-effort of the locomotive will fall off rapidly as the speed increases. Now, since the train resistance increases with the speed, it follows that if a locomotive with an equipment of series motors is designed for operating at a high free-running speed, then the tractive-effort and draw-bar pull at low speeds will probably exceed the limiting values given above unless means are taken to limit the current input to the motors. This characteristic of locomotives equipped with series motors is brought out in Fig. 297,* in which are given the speed-tractive-effort curves of some recent electric locomotives, together with those of some modern steam locomotives for comparison. The difference in the slope of the curves for the steam and electric locomotives is very marked, and the "constant output" feature of the steam locomotive (due to the variable cut-off) is also shown. The electric locomotives to which the curves of Fig. 297 refer were designed for hauling main-line trains over the electrified zone of the New York lines, and in this case the draw-gear is capable of withstanding the large draw-bar pull at low speeds.

. Although it is not our object to discuss in detail the future of main-line electrification, nevertheless we may point out that the curves given in Fig. 297, for the express passenger locomotives, indicate that a machine having a constant-output characteristic (above, say, 20 ml.p.h.) is required for this class of service. This characteristic is possessed by the adjustable-speed shunt motor (*i.e.* a shunt motor with speed variation by alteration of the exciting current). For operation at high voltages the shunt field windings of the motors would have to be excited from the motor-generator used for supplying the lighting and control circuits, and it would also be desirable to provide each motor with a light series field. The speed of the locomotive would then be adjusted by altering the exciting current of the motors, the shunt fields of all the motors being connected in series.†

The polyphase induction motor, wound for a number of poles, also possesses a similar characteristic.

The influence of the wheel arrangement, the height of the centre of gravity, and the disposition of the various parts of a locomotive on its running qualities, is a large and controversial subject, and we propose to consider only what appear to be the chief causes affecting the running qualities and track wear.

In this country nearly all the electric railways are operated with motor-coach trains, on which relatively large motors are carried on the bogies. On those railways (*e.g.* the District and Metropolitan Railways, London) which operate at a high schedule speed, with a short distance between the stations, it has been found that excessive rail wear can only be prevented by the use of specially hard rails of "Sandberg" steel.‡ The excessive rail wear is due to a combination of circumstances,

* Given by Mr. Roger T. Smith in a paper on "Some Railway Conditions Governing Electrification." See *Journal of the Institution of Electrical Engineers*, vol. 52, p. 293.

† The use of motors having a shunt characteristic for main-line fast passenger traffic has recently been suggested by Monsieur H. Parodi and Mr. Roger T. Smith. See *Journal of the Institution of Electrical Engineers*, vol. 51, p. 546; vol. 52, p. 298.

‡ See *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 179, p. 79. See Chapter XX, p. 462, for particulars of "Sandberg" steel.

among which may be included:—The high values adopted for the acceleration and braking, the large number of trains running on the track during the “rush” hours (*e.g.* the service on a portion of the District Railway

H.P., Continuous-current, Side-rod Locomotive
Co.).

FIG 298.—Trucks and Running-gear of

is forty-five trains per hour), the large number of driving axles, the use of wheels of small diameter, and the unsprung-borne load on the driving axles.

With locomotives, the chief trouble with the track is the “spread-

ing" of the rails, due to excessive lateral pressure from the wheel flanges. The lateral pressure is produced by the transverse movement of the locomotive between the track-rails (this motion being termed "nosing") which causes the flanges of the wheels to deliver blows to the side of the rail head. The magnitude of these blows has been determined experimentally* (on the Pennsylvania Railway) with different types of electric and steam locomotives. It was found that the maximum blows (equivalent to a steady force of 11·8 tons) were delivered by electric locomotives of the "gearless" type (see below), having a low centre of gravity, while the minimum blows (equivalent to a steady force of 2·36 tons) were produced by a steam locomotive, the speeds in the tests ranging from 45 to 90 ml.p.h. Other electric locomotives with geared motors and with side-rods arranged in a similar manner to the steam locomotive (see Fig. 298) were also tested, and were found to give results intermediate to the above, the side-rod locomotive, in which the motors were located in the cabs, delivering blows having a maximum value double those delivered by a steam locomotive with the same wheel arrangement and height of centre of gravity. Generally, for running at high speeds, it has been found that the locomotive must be equipped with a leading bogie, and this is in accordance with steam locomotive design.

Methods of Transmitting the Power from the Motors to the Driving Wheels.—There are three general methods adopted for transmitting the power from the motors to the driving axles, and electric locomotives, therefore, can be divided into three classes, viz. (1) the "gearless" locomotive, in which the armatures of the motors drive the axles direct; (2) the "geared" locomotive, in which the axles are driven through gearing; (3) the "side-rod" locomotive, in which the axles are driven through side connecting-rods.

The **gearless locomotive** can be divided into two sub-classes, according to the manner in which the armature is carried on the axle. Thus the armature may be pressed directly upon the axle, with a special bi-polar† field frame incorporated in the truck, and so arranged that the armature may have vertical play without striking the pole-faces (see p. 365); or, alternatively, the armature may be fixed to a hollow sleeve or "quill" which surrounds the axle with sufficient clearance to allow for the vertical play of the latter, the torque being transmitted from the quill to the driving wheels through springs, which also tend to maintain the quill and axle in their correct relative positions. The field frame, in this case, must be centred on the quill by suitable bearings, and must be supported from the truck frame.

The **geared locomotive** can also be divided into two sub-classes, which comprise (a) a rigid and (b) a flexible drive as above. In the rigid drive the motor is supported on the truck and the axle in the manner shown in Fig. 280 (p. 334). This method is used extensively with continuous-current locomotives operating at low and moderate

* See *Journal of the Institution of Electrical Engineers*, vol. 51, p. 548.

† With a multipolar field frame it is necessary to support the frame on the axle in order to maintain the armature and field in the correct relative positions (assuming the truck frame to be spring-supported from the axle boxes). If the truck frame is supported directly on the axle boxes without springs, then the frames of the motors can be fixed to the truck frame and no axle supports are required.

speeds. When large motors (of 300 H.P.) are used on slow-speed locomotives, it is the practice to fit twin gears, one at each side of the motor, as shown in Fig. 310 (p. 377), as by these means the pressure on the teeth is more uniform than when a single gear is used, and consequently higher tooth pressures may be adopted.*

The flexible drive has been developed for single-phase motors, to overcome the vibration due to the pulsating torque, and in this case the gear-wheel is mounted on a quill and drives the wheels through springs (see Fig. 316), the motor being supported from the truck frame and centred on the quill.

The **side-rod locomotive** has received its greatest development from Continental engineers, and numerous designs have been evolved, some of which have been successful. The object of this type of locomotive is to enable one or two large motors to be used instead of a number of smaller machines. The motors are located in the cab, and drive the wheels from the outside by means of cranks and side rods, a suitable number of wheels being coupled together to obtain the adhesion required. In this manner a high centre of gravity is secured, and the axles are relieved of heavy non-spring-borne loads. One form of drive, which is adopted on the 4000-H.P. **Pennsylvania locomotives**, is shown in Fig. 298, while the completed locomotive is illustrated in Fig. 314. It will be seen that the locomotive is built in two halves with the trucks "articulated" (i.e. hinged together). On each truck is mounted a 2000-H.P., 10 pole, 600-volt, continuous-current motor, with a crank at each end of the armature shaft, the cranks being set at right angles to each other. Each crank is coupled, by means of connecting rods, to a transverse crank-shaft (called a "jack-shaft" †) mounted in bearings on the truck frame, and the wheels are driven from the jack-shaft through coupling rods. The connecting-rods between the jack-shaft and the wheels are horizontal, and the wheel arrangement is the same as that of a steam locomotive.

The majority of the Continental designs for the side-rod drive have been developed for single-phase locomotives, using either one or two motors per locomotive. We do not propose to discuss all of these designs in detail, since a large number of them are of an experimental nature.‡ It is necessary, however, to refer to one type of side-rod drive (viz. the "scotch yoke") in which the usual type of connecting-rod is not adopted. For this drive two motors are necessary, which must be arranged on either side of a central axle carrying driving wheels. The armatures are fitted with cranks in the same manner as the above motors, and the crank-pins are connected together, on each side of the locomotive, by an inverted triangular framework, called a "scotch yoke"

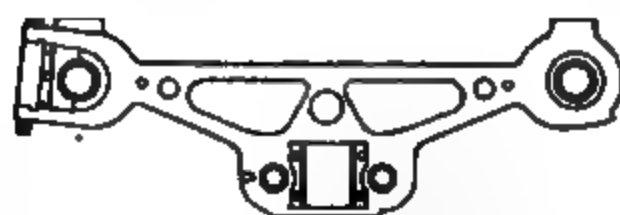
* In some cases springs are inserted between the rims and the hubs of the gear wheels to equalise the stresses between the two sets of gears (see *General Electric Review*, vol. 19, p. 13).

† The jack shaft is necessary since the motors are mounted on the locomotive framing, which is spring-supported on the axles. With a horizontal drive from the jack shaft to the driving wheels, the vertical motion of the latter, due to irregularities in the track, has only a very small effect on the distance between the centres of the crank-pins, and is provided for by the clearance between the axle boxes and the guides.

‡ A number of designs are given in the papers on "Electric Locomotives" by Mr. F. Lydall (*Journal of the Institution of Electrical Engineers*, vol. 51, p. 739; vol. 52, p. 381).

(see Fig. 299). In the apex of this framework is a vertical slot, in which slides a block forming the bearing of one of the crank-pins on the central driving wheels. The rotation of the armature is, therefore, imparted to the driving wheels through the slotted crank-pin bearing, and the slotted connection allows for the vertical motion of the axle relative to the motors, since the latter are mounted on the locomotive framing. The other driving wheels are driven from the centre of the scotch yoke by coupling rods (see Figs. 320, 338, 339, 340).

This drive possesses the advantages of fewer parts and a lighter mechanical construction than the connecting-rod drive in which a jack-shaft is used. On the other hand, the direct drive with scotch yokes can only be used for motors in which the armature diameter does not exceed that of the driving wheels. (This will be apparent from an



Detail of Scotch Yoke

FIG. 299.—Diagram of the Scotch-yoke Drive.

inspection of Fig. 299.) With three-phase motors this restriction does not present any serious drawback, since motors rated at 1000 H.P. can be used with 42-in. driving wheels. Single-phase motors, however, require a much larger armature diameter than three-phase machines, and consequently they cannot be mounted in this manner, as very large driving wheels (and therefore a very slow speed motor) would be required. In this case it is necessary to introduce gearing between the motors and the scotch yokes, the latter being driven from jack-shafts geared to the armatures (see Fig. 321).

When a number of axles are driven through side coupling-rods, it is essential that all the former should remain substantially parallel. In order to enable locomotives having five coupled axles to negotiate curves, the outer driving axles must be allowed considerable end-play—from 1 in. to 1½ in., depending on the wheel-base and curvature of track—the central axle must either be allowed end-play or be provided with wheels without flanges, and the inner pair of driving axles must have no end-play.

Discussion on the above methods of power transmission.—Before discussing the electrical equipment of locomotives, it will be desirable to consider the limitations and characteristic features of the above methods of transmitting the power from the motors to the driving axles.

First let us investigate the **limitations of the geared locomotive.** We have already shown (Chapter IV) that the size of the motor, when mounted in the usual manner, is limited by the diameter of the driving wheels. With wheels 48 in. in diameter a continuous-current motor rated at 300 H.P. can be accommodated, and with 60-in. wheels a motor of probably 500 H.P. could be accommodated.*

Assuming that the size of the motor presents no difficulty, we have still to consider the gearing. The limitation here is the peripheral speed of the pitch circle, which, at the maximum speed of the locomotive, should not exceed 2500 to 3000 ft. per minute for spur-gearing with straight teeth.† This limiting speed must also be considered in relation to the limiting peripheral speed of the armature, which is generally about 7500 ft. per minute for continuous-current railway motors.‡

When the size of the driving wheels and the maximum speed of the locomotive are fixed, the maximum diameter of the pitch circle of the gear-wheel can be obtained by assuming an appropriate value for the limiting gear velocity. This diameter, however, must provide sufficient clearance between the bottom of the gear-case and the track,§ which is generally the limiting feature in slow and moderate speed locomotives. The maximum gear ratio and the peripheral speed of the armature can then be obtained when the distance between the centres of the axle and armature shaft is known.

Now the object of the gear drive is to enable a motor running at a moderate speed to be used, and a little consideration of the above limitations will show that, when high speeds are required, a high gear velocity must be adopted if motors of large size are to be used. This will be apparent from the following example. Suppose we have a large geared motor, having an armature diameter of 30 in., which requires driving wheels of a minimum diameter of 60 in., the distance between the centres of the armature and axle being 29 in. First consider the use of this motor on a locomotive for which the maximum speed is, say, 45 ml.p.h. Then, assuming a maximum gear velocity of 3000 ft. per minute, we have—

$$\text{Maximum diameter of pitch circle of gear wheel} = \frac{3000}{3960} \times 60 = 45.5 \text{ in.}$$

$$[45 \text{ ml.p.h.} = 3960 \text{ ft. per min.}]$$

$$\text{Hence the minimum diameter of the pinion} = 2 \left(29 - \frac{45.5}{2} \right) = 12.5 \text{ in.,}$$

$$\text{and the maximum gear ratio} = \frac{45.5}{12.5} = 3.64 : 1.$$

* The three-phase locomotives built by the General Electric Co. for the Cascade Tunnel have 60-in. driving wheels and geared motors rated at 500 H.P.

† For helical gearing these speeds can be increased considerably. Thus, for the triple-helical gears on the Lötschberg locomotive (Fig. 320), the gear velocity at the maximum locomotive speed is 4500 ft. per minute.

‡ With large single-phase motors the limiting peripheral speed of the armature is, in some cases, of the order of 10,000 ft. per minute.

§ For approximate purposes the maximum diameter of the gear wheel may be assumed at from 75 per cent. to 80 per cent. of the diameter of the driving wheel.

The peripheral speed of the armature, corresponding to a locomotive speed of 45 ml.p.h., will be—

$$3960 \times 3.64 \times \frac{30}{60} = 7220 \text{ ft. per minute,}$$

which is practically equal to the limiting value given above.

Thus, we have the limiting gear velocity and the limiting armature speed both occurring at the same locomotive speed, so that the full advantage of the geared motor is obtained.

Let us now consider the possibility of using this motor on a locomotive for which the maximum speed is, say, 65 ml.p.h. Then, assuming the maximum gear velocity to be 3000 ft. per minute (as above), we have—

$$\text{Maximum diameter of pitch circle of gear wheel} = \frac{3000}{5720} \times 60 = 31.5 \text{ in.}$$

$$[65 \text{ ml.p.h.} = 5720 \text{ ft. per minute.}]$$

$$\text{Hence the minimum diameter of the pinion} = 2 \left(29 - \frac{31.5}{2} \right) = 26.5 \text{ in.,}$$

$$\text{and the maximum gear ratio} = \frac{31.5}{26.5} = 1.19 : 1.$$

The peripheral speed of the armature, corresponding to a locomotive speed of 65 ml.p.h., will be—

$$5720 \times 1.19 \times \frac{30}{60} = 3400 \text{ ft. per minute,}$$

which is less than half of the limiting value given above.

A higher peripheral speed of the armature can be obtained either by increasing the gear velocity and employing some method of forced lubrication, or by increasing the diameter of the driving wheels. But, by the use of a smaller motor, we can arrange for the limiting armature speed to be reached at the same time as the limiting gear velocity. Thus for a motor with an armature diameter of $18\frac{1}{2}$ in., the distance between the centres of the armature and the axle is 16.5 in. With this motor and 48-in. driving wheels, the peripheral speed of the armature (corresponding to a locomotive speed of 65 ml.p.h. and a gear ratio of 3.22 : 1) is 7100 ft. per minute.

Limitations and characteristic features of the gearless motor.—When the armature is mounted directly upon the axle, the full distance between the wheel flanges can be utilised for electrical purposes by adopting a two-pole design, but with a multipolar design or a flexible drive the bearings for the frame will require about 25 per cent. of this distance. Hence the two-pole motor will allow of the use of smaller driving wheels than a multipolar machine, thereby leading to a more economical design on account of the higher armature speed.

As an example we may consider the motors on the original New York Central locomotives, which were designed for a maximum operating speed of 65 to 70 ml.p.h. The motors are of a special two-pole type (see Fig. 300), in which the armature and commutator occupy the whole distance between the wheel flanges. They are rated at 550 H.P., and the respective diameters of the wheels and armatures are 44 in. and 29 in. The adoption of a multipolar design or a flexible drive would have necessitated an increase in the armature diameter (on account of

the bearings for the frame requiring about 25 per cent. of the distance between the wheel flanges), and a still larger increase in the diameter of the driving wheels. It is clear that, under these circumstances, the multipolar design will lead to a heavier and more costly machine than



Plan & Longitudinal Section

FIG. 300.—General Arrangement of 2-pole, Gearless Motor. (Developed for New York Central Locomotives.)

a two-pole design. There are limits, however, to the maximum size of motor which can be carried directly upon the axle. Firstly, the low centre of gravity will probably result in bad riding qualities, and, secondly, a large dead weight on the axles will lead to increased track wear at cross-overs and junctions. These considerations appear to limit

the size of this type of motor to about 500 H.P., since the motors on the recent New York Central locomotives are rated at 330 H.P.

When it is desired to use one or two large motors on a locomotive, the wheels must be driven through side rods, in order that the diameter of the armature shall not be restricted by that of the driving wheels. The motors are then supported on the truck frame, thereby relieving the axles of non-spring-borne load and giving the locomotive better riding qualities, due to the higher centre of gravity. In cases where the diameter of the rotor or armature does not exceed that of the driving wheels, the direct drive through scotch yokes may be adopted, which has several advantages over the connecting-rod drive with jack-shafts.

We have already stated that numerous designs have been evolved for **side-rod locomotives**, and that some of these have not been successful. An examination of the mechanism of the side-rod drive with connecting rods and jack-shafts will reveal several **fundamental differences** between it and the similar drive adopted on a steam locomotive.

Thus there is no "free end" corresponding to the piston, and consequently the centres between all crank-pins must be rigidly maintained. Any wear in the crank-pin bearings or the bearings of the jack-shaft will therefore result in excessive stresses and bearing pressures.* In order to avoid excessive vibrations from these causes it will be necessary to provide means for the accurate adjustment of the bearings. The parts will also have to be designed to withstand these increased stresses, and in some cases it may be necessary to introduce springs or other devices in the driving mechanism.

Also the conversion of the uniform torque of the motors into a reciprocating motion produces severe stresses in the motor shaft, jack-shaft, and locomotive framing.

Consider first the forces acting on the motor shaft. Since the cranks are set at right angles to each other, there will be four positions in each revolution where the full torque of the motor is transmitted through one crank. Therefore each connecting rod is subjected to an alternating force having a maximum value represented by—

$$\frac{\text{maximum value of torque.} \dagger}{\text{radius of crank}}$$

Now if the forces acting on each crank-pin are resolved in two directions at right angles—one direction being along the line of centres—it will be found that the motor shaft is subjected to reciprocating forces and alternating couples in these directions; the reciprocating forces and couples changing their direction four times in each revolution. These forces act on the motor bearings and frame, and must be taken into account in the design of the machine and the locomotive framing. (Note the rigid frame of the motor illustrated in Fig. 298.)

The jack-shaft will be subjected to greater stresses than the motor shaft, for, in addition to the alternating forces and couples, there is the large twisting moment, due to the transmission of the full power through alternate cranks four times in each revolution. The forces and couples resulting from the connecting-rods and coupling-rods will depend on the

* See an article on "The Crank Drive in Electric Locomotives" by J. Buchli (*The Electrician*, vol. 73, p. 992; *The Engineer*, vol. 120, p. 287).

† With single-phase motors the torque is pulsating, and consequently the maximum or crest value must be used in the above expression.

angle between the former and the latter, the maximum values occurring when this angle is 90 degrees, i.e. when the connecting-rods are at right angles to the coupling-rods. Moreover, the forces at each crank-pin can be resolved into a couple and a force, the axis of the couple and the direction of the force both rotating with the jack-shaft.

It is apparent, therefore, that the jack-shaft, the cranks, and the connecting-rods will have to be exceptionally strong, while the bearings for the jack-shaft must be liberally designed. On several Continental locomotives the jack-shaft has a diameter of 10 in., and special steels are used for the above parts. The mechanical construction of this type of locomotive will, therefore, be more expensive than that of locomotives in which jack-shafts and connecting-rods are not used.*

Another feature which is of special importance with side-rod locomotives, is the large forces to which the transmission gear may be subjected when the armature is stopped suddenly, as for instance when the driving wheels are skidded by excessive pressure of the brake shoes, or when a flash-over occurs at the brushes. There are two methods of preventing damage to the transmission gear under these abnormal conditions, viz. (1) to arrange that the armatures shall slip round on their shafts whenever the torque exceeds a predetermined value; (2) to design all the running parts to withstand the stresses under these abnormal conditions. The first method is adopted in the Pennsylvania locomotives, and has given satisfactory results in practice, except that the mechanical balance has to be readjusted after a slip occurs. The second method has been adopted for the majority of the Continental locomotives in which the mechanical parts are designed with sufficient strength to enable the motors to slip the driving wheels when the coefficient of adhesion is 0.33.

The limiting speed of a side-rod locomotive is governed by the permissible angular velocity of the crank shafts and the limiting peripheral speed of the armature. Experience on the Continent shows that rotative speeds of from 450 to 500 r.p.m. are practicable with electric locomotives, owing to the possibility of accurately balancing the rotating parts. These values may be considered as the limiting values of the angular velocity of the armature, and since the diameter of the armature is not restricted by that of the driving wheels, we can make the limiting peripheral velocity coincide with the limiting angular velocity and secure an economical design. Thus, if the limiting angular and peripheral velocities be assumed as 475 r.p.m. and 7500 ft. per minute respectively, then, for a maximum locomotive speed of 80 ml.p.h., the diameter of the driving wheels will be 56.5 in., while the maximum diameter of the armature will be 60 in. If the maximum locomotive speed is of the order of 50 ml.p.h., then it will be necessary to adopt a lower value for the limiting angular velocity, as the above value will lead to small driving wheels. Assuming the minimum diameter of the

* In a paper on "Electric Locomotives," Mr. F. Lydall, after discussing the breakages of the connecting-rods on some Continental side-rod locomotives, concludes with: "Partly for this reason and also on other grounds connected with the first cost, there is a tendency at present on the Continent towards the use of gearing rather than connecting-rods for transmitting the torque to the jack-shaft or direct to the axles. If the author (of the paper) is not mistaken, this is also the general conclusion in the United States, where the connecting-rod drive does not find much favour" (*Journal of the Institution of Electrical Engineers*, vol. 52, p. 384).

A large number of continuous-current geared locomotives have the body constructed with a central cab (forming the driver's cabin) and two sloping ends. The compressor, blower, master controllers, brake valves, circuit-breakers and switches are located in the central cab; while the contactors, reversers, rheostats and brake reservoirs are located in the sloping ends. This arrangement of the apparatus is indicated diagrammatically in Fig. 301, which refers to the Detroit River Tunnel locomotives described below.

In some cases, however, the compressor and blower are located in the sloping ends, while the contactors, rheostats, and other control apparatus are located in the cab. This apparatus is then arranged on a steel structure with expanded-metal screens, and is located in the centre of the cab (see Fig. 302), so that each part is readily accessible for inspection. The illustrations in Fig. 302 refer to standard 60-ton locomotives of the Westinghouse Co., and provide an excellent example of compactness and accessibility. The control apparatus is of the electro-pneumatic type: on the floor are located the reverser, control-circuit rheostat, and the distributing valve for the air brake; the centre tier carries the "switch group" and the circuit-breaker (or "line switch"); while the top tier carries the rheostats. The rheostat compartment is enclosed with sheet steel doors which extend to the roof, and the latter is provided with ventilators, so that an effective circulation of air through the rheostats is obtained. The master controller and the driving position are also shown in the illustrations.

The body of single-phase locomotives is usually of the box or coach type, and contains the whole of the control and auxiliary apparatus, while the interior is divided into compartments, to separate the high-tension apparatus.

EXAMPLES OF ELECTRIC LOCOMOTIVES *

The following examples are representative of modern continuous-current and alternating-current locomotives. Detailed descriptions of the motors, control and auxiliary apparatus are not included, as a large portion of this equipment is described elsewhere (see Chapters IV, V, VI, IX, X, XI, XIV).

Continuous-current Locomotives.—Two examples of geared locomotives, which are in service on the **Metropolitan Railway** (London), are illustrated in Figs. 303, 304. Each locomotive has a nominal weight of 50 tons, and is designed for handling non-electrified rolling stock and goods trains, the load being limited to a maximum of 250 tons. In order to provide for the two types of brakes (viz. the vacuum and the air-brake) in use on the rolling stock, an air compressor and vacuum pumps are included in the equipment of each locomotive. A reference to Figs. 303, 304 will show that the body is mounted on two bogie-trucks with swing bolsters, and the draw- and buffing-gear are built into the underframe. The whole tractive-effort of each bogie must, therefore, be transmitted through the centre-pins to the underframe. Each truck is equipped with two 200-H.P., 600-volt, geared motors, and collector shoes.

* The principal dimensions, weights, and other data of the locomotives discussed here are given in tabular form at the end of this chapter.

In the locomotive equipped by the **B. T.-H. Co.** (Reference No. 1, Table XIII), each pair of motors is controlled on the series-parallel system, and the two pairs are controlled on the multiple-unit system (Type M control), as described in Chapter IX. A master controller, together with the brake valves and gauges, is installed at each end of the cab, as shown in Fig. 305, while the contactors, reversers, and rheostats for each pair of motors are located on each side of the cab, as shown in Fig. 306, thereby providing a central gangway and facilities for inspection. A switch panel is fixed at one end of the cab and carries the main switches for the motor circuit, together with the switches and fuses for the control circuits, pumps, compressor, and lighting.

FIG. 303.—**B.T.-H. 50-ton Continuous-current Locomotive** (Metropolitan Railway, London).

In the locomotive equipped by the **British Westinghouse Co.** each pair of motors is controlled by a group of electro-pneumatic contactors of the type illustrated in Fig. 158 (p. 186), and the two groups are controlled on the multiple-unit system. The central portion of the cab contains the master controllers, brake valves, motor-generator sets for supplying the control circuit, switches for the control and main circuits, main circuit-breakers, and reversers. The vacuum pumps, air reservoirs, contactor groups, and rheostats are located in the sloping ends, while the compressor is located underneath the body between the trucks.

Another example (Reference No. 2, Table XIII) of this class of locomotive, equipped by the **B. T.-H. Co.**, is shown in Fig. 307. This locomotive is in service on the **North-Eastern Railway** (Tyneside electrified section) for handling goods traffic, and is provided with collector shoes and a pantagraph collector. [The overhead construction is used in yards where, on account of the complicated trackwork, conductor rails would be inadmissible.]

The above types of locomotives fulfil the requirements for goods traffic in this country, since the draw-bar pull is limited to about 14 tons, on account of the draw-gear on the wagons. In America, how-

ever, the automatic coupling (wherein the buffing- and draw-gear are combined) is largely adopted in combination with continuous air-brakes; and since this type of coupling will withstand safely a draw-bar pull of between 30 to 40 tons, it is possible to run very heavy trains, the weight of the train in some cases reaching 4000 tons. Under these conditions a very powerful locomotive is required, and, to relieve the underframe and bogie centres from excessive stresses, the buffing- and draw-gear must be incorporated with the trucks or locomotive framing, according to the manner in which the motors are mounted. When

FIG. 304.—British Westinghouse 50-ton Continuous-current Locomotive
(Metropolitan Railway, London).

bogie trucks equipped with motors are adopted, they must be articulated or hinged together in order that the tractive-effort of the leading truck may be transmitted to the draw-gear. It is apparent, therefore, that the body of the locomotive cannot be connected to both trucks by centre-pins (as in the above locomotives), since the distance between the truck centres will vary with the radiation of the trucks. This difficulty is overcome by the use of a standard centre-pin on one truck and a special centre-bearing on the other truck, this bearing allowing swivelling and longitudinal sliding motions to take place.

An example of a locomotive, designed and equipped by the **General Electric Company** (of America), in which these features are embodied, is shown in Fig. 308. The locomotive (Reference No. 3, Table XIII)

has a nominal weight of 90 tons, and is intended for moderate-speed heavy passenger and goods traffic, several locomotives being in service on the lines running through the Detroit River and Baltimore tunnels:

The trucks are illustrated in Fig. 309, and differ considerably from the types previously discussed, the bolster being bolted directly to the side-frames. In order to secure easy riding, and to distribute

FIG. 305.—Driving Position, B.T.-H. 50-ton Locomotive. NOTE.—The operating valve for the Westinghouse (compressed-air) brake is shown to the left of the master controller, and the operating valve for the vacuum brake is shown to the right. The instruments include: a vacuum gauge, a duplex-pressure gauge, and an ammeter.

the weight equally between the axles, a compound-equalised spring system is adopted. The whole weight of the body and truck frames is carried on semi-elliptic springs, which rest on saddles fixed to the axle-boxes. The springs on the forward truck (with the fixed bogie centre, shown on the right-hand side of Fig. 309) are equalised longitudinally—that is, the inner ends of the springs are connected together by equalising bars pivoted to the side-frames, thereby equalising the weight between

the wheels of this truck. On the other truck the springs adjacent to the hinge joint are connected directly to the truck frame, while the other pair are cross-equalised, the extreme ends being connected together by a transverse equalising bar pivoted to the truck frame. The outer end-frames carry the buffing- and draw-gear, while the inner end-frames are connected together by a hinge joint, which is designed so that the rear truck can resist any tilting action of the forward truck.

Each axle is geared to a 300-H.P., 600-volt, commutating-pole, forced-ventilated motor arranged with twin gears, the gear wheels being mounted on projections provided on the wheel centres. An outline drawing of the motor is shown in Fig. 310. The torque of each motor at the rated load is 4000 lb.-ft., which, with 48-in. wheels and a gear

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FIG. 306.—Interior of B.T.-H. 50-ton Locomotive.

ratio of 4.37 : 1, corresponds to a tractive-effort of 8750 lb. The four motors are capable of developing a total tractive-effort of 15.6 tons at a speed of 12 ml.p.h., and have sufficient overload capacity to exert a momentary tractive-effort of about 25 tons.

The four motors are controlled on the double series-parallel system with multiple-unit Type M control apparatus. A total of 24 notches is provided, viz. 9 notches with the motors in series, 8 notches with the motors in series-parallel, and 7 notches with the motors in parallel. This large number of notches is provided in order that the variation in the tractive-effort when passing from notch to notch shall be small, so that slipping of the driving wheels shall not occur when the locomotive is accelerating a heavy train. The contactors on each locomotive number 43, of which 16 (viz. 4 for each motor) are used as reversing switches. Coupler sockets are provided, so that two or more locomotives may be operated together on the multiple-unit system.

Each driving end of the cab is provided with a master controller, brake valve, ammeter, and gauges, while at the centre of the cab are

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FIG. 307.—B.T.-H. 56-ton Continuous-current Freight Locomotive.

FIG. 308.—General Electric 90-ton Continuous-current Locomotive for Moderate Speed, Heavy Passenger and Freight Traffic.

located the air-compressor and blower. The contactors, together with the other portions of the control and brake apparatus, are located in the sloping ends, as indicated in Fig. 301.

An example of a high-voltage continuous-current locomotive is illustrated in Fig. 311 (Reference No. 4, Table XIII), which shows one of the locomotives supplied by the General Electric Company of America to the **Butte, Anaconda and Pacific Railway**. Fifteen locomotives are in service for freight traffic, and two locomotives coupled together can handle a train weighing 4150 tons. Each locomotive has a nominal weight of 71.5 tons, and is of the articulated, equalised, double-truck type, the trucks being similar to those on the locomotive just described. Each axle is geared to a 300-H.P., 1200-volt, commutating-pole forced-ventilated series motor fitted with twin gears. The torque of each motor at its rated load is 2970 lb.-ft., which, with 46-in. wheels and a gear ratio of 4.84 : 1, corresponds to a tractive-effort of 7500 lb. The four motors are capable of developing continuously a tractive-effort of 11.1 tons at a speed of 15 ml.p.h., and can exert a tractive-effort of 21.5 tons for five minutes. Each motor is insulated for 2400 volts, and two motors are permanently connected in series, the two pairs being controlled on the series-parallel multiple-unit system (Type M control) by master controllers and contactors, the latter being operated from a 600-volt circuit obtained from a dynamotor, which is combined with the blower. This dynamotor also supplies current to the air-compressor and lighting circuits.

FIG. 309.—Compound-equalised Trucks for 90-ton Locomotive.

The cab is of the box type, and is divided into three compartments, viz. a driving compartment at each end, and a central compartment for the control apparatus and auxiliary machines, the 2400-volt apparatus being located in enclosed chambers. Each locomotive is fitted with two collectors, of the roller pantagraph type, which are connected to a bus-line running along the roof to enable the collectors of two or more locomotives to be connected in parallel. A view of the roof of the locomotive is given in Fig. 312.

An example of a **gearless locomotive** is illustrated in Fig. 313 (Reference No. 5, Table XIII), which represents the 1914 design of locomotive built by the General Electric Company (of America) for the **New York Central Railroad**. In this locomotive (which is designed for express passenger service and is capable of hauling trains weighing 980 tons at speeds up to 60 ml.p.h.) all the axles are equipped with motors of a special bi-polar type, in which the armature is mounted directly on the axle, and the field frame forms part of the truck frame. The general design of the motor is shown in Fig. 300. It will be observed that the armature and commutator occupy practically the whole of the distance between the wheel hubs. The poles are arranged with nearly flat vertical pole faces, so that the vertical movement of the armature and the axle is unrestricted. Each motor is provided with enclosing covers, and is ventilated by a blower located in the cab, the blower supplying 24,000 cubic feet of air per minute to the eight motors. With forced ventilation the one-hour rating of each motor is 330 H.P., while the continuous rating (at 600 volts) is 250 H.P. The speeds of the locomotive corresponding to these ratings are, respectively, 48 ml.p.h. and 54.5 ml.p.h. The maximum speed is 75 ml.p.h., and at this speed the total tractive-effort is 3.15 tons.

The motors on each truck are permanently connected in parallel, and the four pairs are controlled on the double series-parallel system with multiple-unit (Type M control) apparatus. There are 24 notches, viz. 9 "series," 8 "series-parallel," and 7 "parallel."

The "running-gear" consists of four trucks arranged in pairs, each pair being articulated and connected to a frame intermediate between the trucks and the cab. The inner ends of these frames are articulated, while the outer ends carry the buffing- and draw-gear. Thus, as far as the running-gear is concerned, this locomotive is equivalent to two locomotives of the type illustrated in Fig. 308, coupled together by a central coupling. The design has the advantage of the distribution of the load over a long and flexible wheel-base of 46 ft.—the fixed wheel-base being 6 ft. 6 in. for outer trucks and 5 ft. for inner trucks—while the adoption of motors of only a moderate output (330 H.P.) has given the locomotive excellent riding qualities.



FIG. 310.—Outline of G.E. 209, 300-H.P.

Railway Motor fitted with Twin Gears.

FIG. 311.—General Electric 71½-ton, Continuous-current Locomotive in service on the Butte, Anaconda and Pacific Railroad.

The cab is mounted upon centre bearings on the intermediate frames, and is divided into three compartments, of which the two end compartments form driving cabins and the central compartment contains the whole of the auxiliary apparatus, contactors, rheostats, etc.

The **Westinghouse side-rod locomotives** (Reference No.-6, Table XIII) in service on the New York electrified zone of the **Pennsylvania Railroad** have been referred to above (see page 361). The principal mechanical features are shown in Fig. 298; a complete locomotive is

FIG. 312.—View of Roof of 2400-volt Locomotive showing Roller Pantagraph Collector and Bus-line.

shown in Fig. 314; and one of the 2000-H.P. motors is illustrated in Fig. 315.* Each locomotive is capable of developing a tractive-effort of 26·8 tons at speeds up to 25 ml.p.h., and a tractive-effort of $4\frac{1}{2}$ tons at a speed of 60 ml.p.h.

The two motors on the locomotive are controlled, on the series-parallel system (with bridge transition) by electro-pneumatic contactors of the standard Westinghouse type. The master controllers are provided with 31 notches, there being 20 notches for the series connection of the motors, and 11 notches for the parallel connection of the motors.

* Characteristic curves of these motors are given in the *Journal of the Institution of Electrical Engineers*, vol. 54, p. 524.

FIG. 313.—General Electric 112-ton, Gearless, Continuous-current Locomotive.

There are 8 running notches, viz. 4 with the motors in series, and 4 with the motors in parallel; the four speeds in each case corresponding to (1) full field, (2) and (3) shunted field, (4) half-field.

Single-phase Locomotives.—The principal single-phase locomotives which are in service in America * are either of the gearless or the geared types, and in each case the torque of the motor is transmitted to the wheels through springs, the object of the spring drive being to absorb the vibrations due to the pulsating torque of the motors, and to relieve the track from heavy unsprung-borne loads. The gearless type of locomotive (Reference No. 7, Table XIII) is used on the **New York, New Haven and Hartford Railroad** for express passenger traffic, while the geared locomotive (Reference No. 8, Table XIII) is used for local passenger and freight traffic.

In the latest locomotives of each type the spring drive between the quill (on which the armature or gear wheel is fixed) and the driving wheels is practically the same, and is illustrated in Fig. 316, which refers

FIG. 314.—Westinghouse 140-ton, Continuous-current, Side-rod Locomotive.

to the geared locomotive. It will be observed that the springs are of the "hour-glass" type, with each end secured in a steel casting; one of these castings is bolted to a flange on the quill and the other is bolted to lugs on the spokes of the wheel. The springs are arranged in pairs, so that, when transmitting torque from the quill to the axle, alternate springs are in tension and compression. The radial clearance between the quill and the axle is about $\frac{1}{8}$ in.

The cab of the gearless locomotive is of the box type, and is mounted on two equalised trucks in the ordinary manner, the draw-gear being fitted to the underframe. Each truck is fitted with a radial pony axle (to obtain good riding qualities), while the driving axles are each equipped with a 250-H.P., 25 cycle, 220-300-volt, single-phase, forced-ventilated series motor; the armature of the motor being mounted on a quill, on which the field frame is centred by suitable bearings. The field frame is spring-supported from the truck frame, so that there is only a small load on the driving springs.

The motors are designed for operating on continuous and alternating current,† and this dual operation has considerably complicated the

* The Westinghouse Co. have been responsible for the equipment of practically all the single-phase locomotives in America.

† The New Haven trains run into New York City over the New York Central lines, which are electrified on the continuous-current system at 600 volts.

control gear. Two armatures are permanently connected in series, and for continuous-current operation the fields are connected in series with

FIG. 315.—Westinghouse 2000-H.P., 600-volt, 10-pole Railway Motor for Pennsylvania Side-rod Locomotive.

FIG. 316.—Spring Drive for Westinghouse Single-phase Geared Railway Motors.

their respective armatures, while for alternate-current operation the fields are all connected in parallel, in order to reduce the flux and the reactance.

When operating with alternating current the motors are supplied from an auto-transformer, the control being effected by a number of tapplings in the manner discussed in Chapter X, but when operating with continuous current the control is on the series-parallel system.

The **geared locomotives** in service on the New Haven lines (see Figs. 317, 459) are characterised by two special features, viz. (1) the mounting of the gear wheels on quills, from which the axles are driven through springs, (2) the mounting of the motors on the truck frames

FIG. 317.—Westinghouse 98-ton Single-phase Locomotive.

above the axles. The first item has already been discussed, while the method of mounting the motors can be seen from Fig. 318.

On some locomotives, twin-motors—illustrated in Fig. 319—have been adopted, the pinions meshing with a common gear-wheel. This arrangement was adopted to enable a high-speed motor to be used, and it is stated that the twin-motor equipment is lighter and cheaper than that with four motors of the same total output.*

The trucks shown in Fig. 318 are of interest on account of the manner in which the locomotive body is supported. Although centre-pin bearings are fitted to the trucks, their function is only to keep the cab in position, and one bearing is arranged to have a limited longitudinal movement in addition to a swivelling movement on account of the articulation of the trucks. The weight of the cab is spring-supported on eight friction plates (*A*, Fig. 318)—two above each pony axle, and two at the inner corners of each truck—the springs being contained in

* With a given gear velocity and locomotive speed, the twin-motor equipment will enable a higher gear ratio to be adopted than is possible with the single motors, on account of the smaller distance between the armature and axle centres. Hence the twin-motors can be run at a higher speed, thereby resulting in a more economical design (see p. 563).

spring-pockets attached to the under side of the body. Spring plungers are also fitted to the underframe to engage the side bearings *B* above the pony wheels. The springs supporting the body allow for variations in the track without appreciably affecting the distribution of weight on the trucks, while the springs at the side bearings and the friction at the supporting plates effectively prevent any periodic vibration or nosing.

As an example of a geared, side-rod, single-phase locomotive with scotch yokes, we may consider the **Oerlikon locomotives** supplied to the **Lötschberg-Simplon Railway** (Reference No. 9, Table XIII). These locomotives (see Fig. 320) are very powerful, and, at the normal rating, can exert a tractive-effort of 13.3 tons at a speed of 31 m.p.h., while, at starting, a tractive-effort of 17.9 tons can be developed.

The total weight of the locomotive is 107 tons, of which 78.2 tons is carried on the driving wheels. The locomotive framing follows the practice adopted for steam locomotives, and is fitted with leading and trailing radial pony axles, while three of the driving axles are allowed sufficient lateral play to enable the locomotive to negotiate curves.*

The motors are located in the centre of the locomotive (see Fig. 321), and drive two jack-shafts through triple helical gearing (gear ratio 2.23 : 1), the jack-shafts driving the wheels through scotch yokes and coupling rods, as shown in Fig. 321. Each motor has sixteen poles, and is of the compensated series type with commutating poles. The rated output (1½-hour

rating) is 1250 H.P., at 435 volts, 15 cycles, with natural ventilation. Views of a motor are shown in Figs. 322, 323.

* The central axle has an end-play of 25 mm. (1 in.), and the outer driving axles have an end-play of 40 mm. (1.58 in.).

FIG. 318.—Trucks of Westinghouse 98-ton Single-phase Locomotive.

The complete locomotive frame, with the motors in position, is shown in Fig. 324. This view also shows the air-cooled transformers and controllers, the latter being of the drum type, electrically operated, and mounted on the top of the transformers in the manner described in Chapter X. Under normal conditions each motor is supplied by the transformer adjacent to it, but under abnormal conditions the two motors can be supplied from one transformer. Each transformer is provided with twelve tapings on the secondary winding, from which the motors are controlled, while some of these tapings supply also the train lighting, heating, and auxiliary motors on the locomotive.

The body of the locomotive is divided into three compartments. The central compartment contains the main motors, transformers, high-tension chambers, and all the auxiliary motors and apparatus, while the two end compartments form driving cabins, and contain the master controllers, instruments, gauges, brake valves, and hand-brake levers. The two high-tension chambers are adjacent to the driving cabins and are shut off from the main compartment by expanded metal doors, which cannot be opened until the bow collectors are lowered. The key for unlocking these doors is attached to the valve controlling the bows, and it can only be removed when the valve is in the position for lowering the bows. This key serves for unlocking all the doors associated with the high-tension chambers, and it can only be removed from the locks after the doors have been closed. Portions of the roof and sides may be removed, as shown in Fig. 321, to facilitate the repair of any of the apparatus. Views of the motor compartment are shown in Figs. 325, 326; and views of the driver's cabin are shown in Figs. 327, 328.

FIG. 319.—Westinghouse "Twin Motors" for Single-phase Locomotives.

The auxiliary machinery includes three electrically-driven exhaust fans, two of which are for cooling the transformers, while the third is located in the central portion of the roof (see Fig. 321) for ventilating the motor compartment; two electrically-driven air-compressors for supplying the air-brakes; and a motor-generator set with a battery of accumulators, for supplying the control circuit and lighting. The location of this auxiliary machinery is shown in Plates I and II.

A 3000-ampere automatic oil-switch is connected in the circuit of each motor, while the primary of each transformer is controlled by an oil-switch with a double set of contacts, by means of which the high tension circuit is opened and closed through a resistance, thereby avoiding surges in the primary (15,000-volt) winding of the transformer. The primary oil-switch is shown in Fig. 199 (p. 228). Each of these oil-switches is operated by a solenoid, the primary switches being con-



FIG. 320.—Oerlikon 107-ton, 2500-H.P., Single-phase Locomotive.

FIG. 321.—Oerl kon 2500-H.P. Single-phase Locomotive, showing Motors, Jack-shafts, and Scotch Yoke.

FIG. 322.—Oerlikon 1250-H.P., 16-pole, Single-phase Motor (commutator end).

FIG. 323.—Oerlikon 1250-H.P., 16-pole, Single-phase Motor (pinion end).

FIG. 324.—Locomotive Frame showing Motors and Transformers in Position (Oerlikon 2500-H.P. Single-phase Locomotive).

trolled together from a handle on the master controller, while a similar handle controls the motor switches. These handles can be seen in Figs. 327, 328, to the left of the main handle, the reversing handle being to the right. Pilot lamps are fitted into the controller cap-plate to indicate whether these switches are open or closed.

The bow collectors are held up by air pressure in the usual manner, and are controlled by a special cylinder on the master controller; they are each provided with an air-core choking coil, and are connected to each of the high-tension switches. A battery of condensers is connected between the bows and earth in order to relieve the apparatus from pressure rises.

For lighter locomotives, the Oerlikon Co. have developed a **side-rod drive with connecting-rods**, using a jack-shaft and two geared motors. Several locomotives of this type—of 600 H.P. and 800 H.P.—have been built for the **Rhaetian Railway** (Engadine District, Switzerland). A typical locomotive is illustrated in Fig. 329, in which the jack-shaft, the connecting-rod, and the coupling-rods are clearly shown.

The locomotives are each equipped with two motors which are mounted on the locomotive framing, as shown in Fig. 330. The armatures of the motors are geared to a common shaft, from which the jack-shaft is driven through cranks and connecting-rods. Views of a 400-H.P. motor are shown in Fig. 331, in which the special feet (for fitting into the locomotive framing) and the arrangement of the pinion-end bearings should be noted. The two motors on each locomotive are supplied from a single transformer, and are controlled by a motor-driven drum-type controller of the Oerlikon standard type. Twelve operating voltages are provided, ranging from 73 volts to 390 volts in steps of 37 volts.

The cab of the locomotive is of the box type, and is divided into three compartments—two driving compartments, and a central compartment in which the motors, the transformer, the control apparatus, and the auxiliary apparatus are located.

Views of the motor compartment of a 600-H.P. locomotive (Reference No. 10, Table XIII) are shown in Figs. 332, 333, and the driving compartment is shown in Fig. 334.

The locomotives are equipped with vacuum brakes, and the speed of the exhaust motor is controlled by a special controller (shown to the right of the master controller in Fig. 334).

The auxiliary machinery on the 600-H.P. locomotives includes an air-compressor (for supplying the compressed air for operating the bow collectors), a motor-driven exhauster, and a motor-generator set, with a battery of accumulators, for supplying the lighting and control circuits. On the 800-H.P. locomotives a motor-driven blower is also included in the auxiliary machinery, since, in these locomotives, the motors and the transformer are forced ventilated.

Drawings of the 600-H.P. locomotive are given on Plate III, and drawings of the 800-H.P. locomotives are given on Plate IV.

An example of a **side-rod locomotive with a direct drive** is shown in Fig. 335, which illustrates the type of single-phase locomotive recently developed by Messrs. **Brown, Boveri & Co.** In this type of locomotive two motors are mounted on the locomotive framing, and drive the main driving axle through cranks and a double connecting-rod.

FIG. 325.—Motor Compartment of Oerlikon 2500-H.P. Single-phase Locomotive.

FIGS. 327, 328.—Driving Cabin of Oerlikon 2500-H.P. Single-phase Locomotive.

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FIG. 329.—Oerlikon 55-ton, 800-H.P., Single-phase Locomotive (Rhaetian Railway).

Fig. 330.—Framing of Oerlikon 600-H.P. Single-phase Locomotive, showing Motors (gear end) and Transformer.

The driving mechanism is shown diagrammatically in Fig. 336. It will be observed that the driving end of the connecting-rod *A* is slotted, and that the other connecting-rod *B* is connected to it by a pin joint. This drive (which may be called the "double connecting-rod" drive) differs from the scotch yoke in that the crank-pins on the armature shafts are not rigidly connected together.*

Locomotives with the double connecting-rod drive have been supplied to several Continental railways, and for single-phase working the equipment consists of Déri brush-shifting repulsion motors. The speed control is therefore carried out entirely by brush-shifting.

The motors are usually supplied from a transformer at about 1000 volts, and the motors and transformer, together with the auxiliary apparatus, are located in the central compartment of the cab, as shown in Fig. 337, the end compartments forming the driving cabins.

Three-phase Locomotives.—Three-phase locomotives are used in considerable numbers on the **Italian State Railways**, and nearly 200 of these locomotives are in service for passenger and freight traffic. With few exceptions the locomotives are equipped with two three-phase induction motors and a direct drive through scotch yokes. Typical freight and

* The scotch yoke cannot be applied successfully to direct drives from large single-phase motors on account of their large diameter.

FIG. 331.—Oerlikon 400-H.P., 10-pole, 16½-cycle, Compensated-series Motor for Electric Locomotives.

passenger locomotives built by the **Società Italiana Westinghouse** are illustrated in Figs. 338, 339 (Reference Nos. 11, 12, Table XIII).*

The **freight locomotives** (Fig. 338) are each equipped with two 1000-H.P. induction motors, which are controlled on the cascade-parallel system, the synchronous speeds—corresponding to normal frequency ($16\frac{2}{3}$ cycles)—being 14 ml.p.h. and 28 ml.p.h. A number of these locomotives are in service on the Giovi-Genoa lines, on which the gradients are long and heavy, the maximum gradient being 3.5 per cent. The total weight of the locomotive is 60 tons, all of which is on the driving wheels. Two locomotives (one hauling and the other pushing) are capable of handling freight trains weighing 260 tons (excluding the locomotives) over the Giovi lines at a speed of 24.3 ml.p.h. up the gradients. On the return journey (down the gradients) two locomotives are coupled together at the front of the train, and the gradients are descended at a speed of about 30 ml.p.h., with the motors acting as induction (asynchronous) generators. The performance of these freight locomotives has been highly satisfactory, and their adoption on the Giovi lines has enabled the capacity of these lines under steam conditions to be nearly trebled, this increase in capacity being due to the higher speeds and the heavier trains.

The **passenger locomotives** (Fig. 339) are equipped with two 1300-H.P. two-speed induction motors, which are controlled on the changeable-pole cascade-parallel system, so that four running speeds are obtained, these speeds (corresponding to the synchronous speeds at normal frequency, $16\frac{2}{3}$ cycles) being 23.3, 31, 46.6, 62 ml.p.h. The weight of the complete locomotive is 71 tons, of which from 50 to 44 tons is adhesive weight. The variation of the adhesive weight is obtained by transferring weight from the driving axles to the pony axles.

The shafts of the motors are supported in bearings carried in special supports from the locomotive frame,† and the concentricity of the stator and rotor is obtained by bearings located in the frame-heads of the motor (see Fig. 88, p. 115).

The tractive-effort of the locomotive—corresponding to the rated load of the motors—at the four running speeds is as follows :—

Connection of Motors.	Synchronous Speed (ml.p.h.).	Tractive-effort (lb.).
8-pole, cascade	23.3	19,800
6-pole, cascade	31	19,800
8-pole, parallel	46.6	20,900
6-pole, parallel	62	13,200

The three-phase locomotives built by **Messrs. Brown, Boveri & Co.** for the **Simplon Tunnel** electrification are of two types, one type

* The motors and control equipment of these locomotives have been discussed in detail in Chapters VI, XI.

For interesting data relating to the Giovi lines and the performance of the electric locomotives, see *The Engineer*, vol. 117, pp. 89, 115, 143, 174, and *The Electric Journal*, vol. 11, p. 550.

† See *The Engineer*, vol. 116, p. 216, for details of these supports.

Figs. 332, 333.—Motor Compartment of Oerlikon 600-H.P. Single-phase Locomotive.

FIG. 334.—Driving Cabin of Oerlikon 600-H.P. and
1800-H.P. Single-phase Locomotives.

FIG. 335.—Brown, Boveri 90-ton, 1500-H.P., Single-phase Locomotive
(Midi Railway).

having a scotch-yoke drive, and the other type having a special coupling-rod drive. A locomotive with the scotch-yoke drive is shown in Fig. 340, and a locomotive with the coupling-rod drive is illustrated in Figs. 341, 342. This locomotive (Reference No. 13, Table XIII), is of particular interest on account of the mechanical and electrical design.

The mechanical design of the locomotive has several unusual features. Thus (1) the motors are located in the centre of the locomotive, clear of the driving axles, which construction permits the motors to be removed *from below*; (2) the coupled wheel-base is exceptionally long, viz. 26.2 ft. (8000 mm.). Of this wheel-base 15 ft. is rigid, the outer wheels being arranged so that a limited transverse, as well as a radial, motion of the wheels can take place. In order to maintain the parallelism of the coupled axles, the outer axles are mounted in bearings fixed to the locomotive framing, and the wheels are mounted on a quill. The latter is connected to the centre of the axle by a special coupling which permits of a limited longitudinal and radial movement of the quill relatively to the axle, the load being also carried at this point. The quill is normally maintained in its correct position by springs. These details of the mechanical design are shown in the drawings of the locomotive on Plate V.

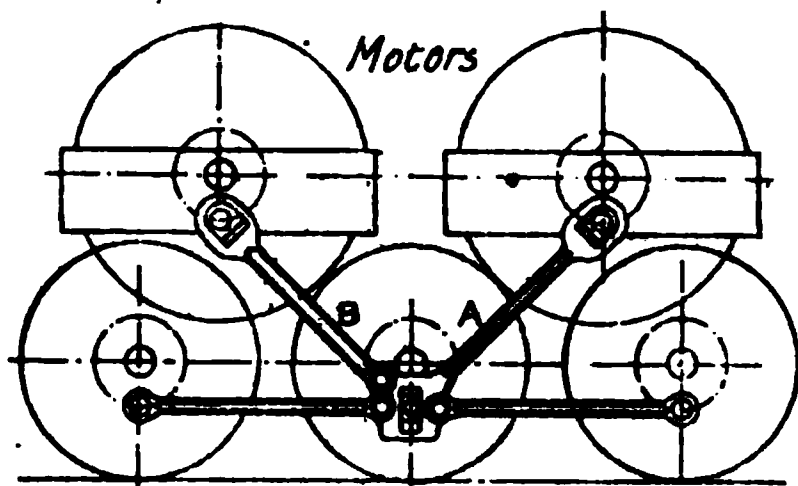


FIG. 336.—Diagram of Brown, Boveri Double Connecting-rod Drive.

The motors are of the four-speed squirrel-cage type, and have been described in Chapter VI.

The body of the locomotive is arranged with a central cab and sloping ends. In the sloping ends are placed the auxiliary machines (such as the air-compressor and the motor-generator for supplying the train lighting) and the auto-transformers for controlling the speed of the motors. The remainder of the control equipment is arranged in cabinets on the sides of the cab (see Fig. 343), so that a clear floor is obtained.

Each pole-changing switch is combined with circuit-breaking oil switches (see Fig. 343), and the latter are arranged so that they are electrically tripped on overloads. Therefore when the two windings of each motor are connected in parallel, each winding is protected against overload.

The tappings on the auto-transformers are connected to drum-type controllers, by means of which various voltages from 1000 to 3000 volts (in steps of 200 volts) may be applied to the motors. The controllers are worked by hand from the driving platform, the four controllers being connected by chain gearing.

A view of the driving platform is shown in Fig. 344.

Split-phase locomotives.—The term “split-phase” locomotive refers to a locomotive operating from a single-phase supply system, in which the driving motors are of the three-phase induction type, and are supplied with polyphase current, at the supply frequency, from a phase-converter.

The special feature of the split-phase locomotive is that the functions of the phase-converter are reversible, and therefore regenerative

FIG. 337.—Brown, Boveri 55-ton, 700-H.P., Single-phase Locomotive, with side removed to show Motors and Transformer (Rhætian Railway).

FIG. 338.—Società Italiana Westinghouse 60-ton, 2000-H.P., Two-speed, Three-phase Freight Locomotive (Italian State Railways).

braking can be obtained in the same manner as with three-phase locomotives.

Locomotives of the split-phase type have recently been developed by the **Westinghouse Co.**, and a number of large locomotives are in

FIG. 339.—**Società Italiana Westinghouse 71-ton, 2600-H.P., Four-speed, Three-phase Passenger Locomotive (Italian State Railways).**

FIG. 340.—**Brown, Boveri 62-ton, 900-H.P., Two-speed, Three-phase Locomotive.**

service on the single-phase system of the **Norfolk and Western Railway, U.S.A.** These locomotives are of interest, not only on account of the method of supplying the (three-phase) motors from a single-phase

FIG. 341.—Brown, Boveri 67-ton, 1700-H.P., Four-speed, Three-phase Locomotive.

FIG. 342.—Brown, Boveri 67-ton, 1700-H.P., Four-speed, Three-phase Locomotive (end view).

supply system, but also on account of the method of transmitting the power from the motors to the driving axles.

A double locomotive-unit (Reference No. 14, Table XIII) is illustrated in Fig. 345. The cab is of the box type, and is supported on two articulated trucks in a manner similar to that adopted in the New Haven freight locomotives (see p. 383). Each truck is equipped with two 410-H.P., three-phase, induction motors * with wound rotors, the wind-

FIG. 343.—Control Apparatus (for one motor) on Brown, Boveri 1700-H.P., Four-speed, Three-phase Locomotive. NOTE. —The combined circuit-breaking and pole-changing switches are located in the upper cabinets, while the reverser is located in the central cabinets.

ings being arranged to give either 8 poles or 4 poles. The rotors are geared to a common jack-shaft through twin gearing, as shown in Fig. 346. The gear wheels on the jack-shaft are provided with cranks from which the driving wheels are driven through horizontal coupling-rods.

Each double locomotive weighs 240 tons, and is capable of hauling a train weighing 2900 tons (trailing load) † up a 1 per cent. grade at a

* The motors are described in Chapter VI. Further details of the equipment will be found in the *Electric Journal*, vol. 13, p. 473.

† These trains consist of steel cars loaded with coal, each car carrying approximately 50 tons of coal.

speed of approximately 14 ml.p.h. (this is the synchronous speed corresponding to the 8-pole winding of the motors). A train weighing 1800 tons can be taken down a 2 per cent. grade at a speed of, approximately, 28 ml.p.h. by a double locomotive, the train being braked electrically.

The double locomotive is capable of exerting a tractive-effort of 60 tons with the 8-pole connection of the motors, and a tractive-effort of 40 tons with the 4-pole connection. The maximum guaranteed output from the eight motors on a double locomotive is 5000 H.P.

FIG. 344.—Driving Platform of Brown, Boveri 1700-H.P., Four-speed, Three-phase Locomotive.

with the 8-pole connection, and 6700 H.P. with the 4-pole connection.

The phase-converter from which the motors are supplied is illustrated in Fig. 347. The converter is virtually a two-phase induction motor with a squirrel-cage rotor, and is started by a single-phase commutator motor (shown to the left in the illustration). The shaft extension on the right carries a 36-in. Sirocco fan for ventilating the motors and the phase-converter.

The general principle of the phase-converter is that, if one phase of a polyphase induction motor is supplied with single-phase current after the rotor has been brought up to speed, the magnetic reactions will produce a rotating field, which will induce E.M.F.s in the other stator windings of exactly the same phase relations as if these windings

had been supplied with polyphase current. Thus with a two-phase winding, if one phase is supplied with single-phase current, then, when the rotor is running, the E.M.F. induced in the open phase will

FIG. 345.—Westinghouse 240-ton "Split-phase" Locomotive (Norfolk and Western Railway).

have a phase-difference of 90 degrees from the voltage on the other phase.

The application of a two-phase converter to three-phase motors is shown diagrammatically in Fig. 348. The main transformer is shown

at *T*, and the centre point of the secondary winding (*C*) is connected to one of the stator windings (*D*) of the phase-converter, the other end of

FIG. 346.—Truck with Motors and Gear-driven Jack-shaft for Norfolk and Western Locomotive.

FIG. 347.—Phase-converter for Split-phase Locomotive.

this winding being connected to one of the terminals (*F*) of the three-phase motor. The other terminals (*G*, *H*) of this motor are connected

to the terminals (*A*, *B*) of the secondary winding of the transformer, to which terminals are also connected the second stator winding (*E*) of the phase-converter. Now, when the phase-converter is in operation, there is induced in the winding *D* an E.M.F. which has a phase-difference of 90 degrees from the E.M.F. at the terminals *A*, *B* of the transformer. Hence, by arranging that the E.M.F. induced in phase *D* shall be $0.866 (= \frac{1}{2}\sqrt{3})$ of the E.M.F. across *A*, *B*, we have—by connecting *D* to the centre point (*C*) of the transformer—the same conditions as exist in the standard method of three-phase to two-phase transformation. Therefore three-phase current may be obtained from the terminals *A*, *B*, *F*.

As actually constructed the phase-converter is more complicated than we have indicated above, since features must be incorporated into its design for annulling the inductive effects due to the load current in phase *E*; while, in order to maintain balanced three-phase voltages under load, the tapping (*C*) on the transformer must be shifted from the centre point of the winding.

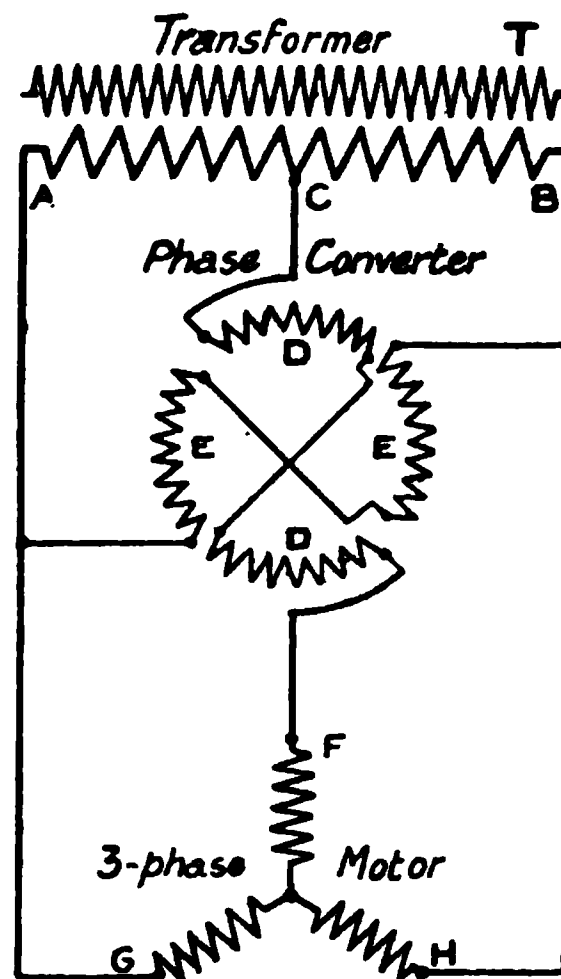


FIG. 348.—Diagram of Circuits of Phase-converter.

For further details of the theory and application of the phase-converter see the following articles and papers:—

“Induction Machines for Heavy Single-phase Motor Service” (a paper by Mr. E. F. W. Alexanderson), *Transactions of the American Institute of Electrical Engineers*, vol. 30, p. 1357.

“Phase-balancer for Single-phase Loads on Polyphase Systems,” *General Electric Review*, vol. 16, p. 962.

“Single-phase Loads from Polyphase Systems,” *Electric Journal*, vol. 13, p. 261.

TABLE XIII

DATA OF ELECTRIC LOCOMOTIVES (4' 8½" GAUGE†)

Reference Number	1	2	3	4	5	6	7	8	9	10†	11	12	13	14
Name of Railway	Metro- politan (London)	North- Eastern	Detroit River Tunnel	Butte, Anaconda and Pacific	New York Central	Pennsyl- vania	New York, New Haven, and Hartford	New York, New Haven, and Hartford	Lötsch- berg Simplon	Rhaetian	Italian State	Simplon Tunnel	Norfolk and Western	
Class	0-4-4-0 AA+AA *	0-4-4-0 AA+AA	0-4-4-0 AA+AA	0-4-4-0 AA+AA	4-4-4-4 AA+AA +AA+AA	4-4-4-4 2-B+B-2	2-4-4-2 1-AA +AA-1	2-4-4-2 1-AA +AA-1	2-10-2 1-E-1	2-8-2 1-D-1	0-10-0 0-E-0	2-6-2 1-C-1	0-8-0 0-D-0	2-4-4-2 1-B+B-1 (one unit)
Type	bogie	bogie	articul- ated bogie	articul- ated bogie	double ar- ticulated bogie	articulated	articul- ated	articul- ated	..	..	..	..	..	articul- ated
Length of framing	30' 0"	35' 0"	39' 6"	37' 4"	56' 10"	64' 11"	36' 4"	50' 0"	48' 3"	29' 9"	31' 3"	36' 0"	34' 0"	52' 10" (one unit)
Width over all	8' 7"	8' 8"	10' 2"	10' 0"	10' 0"	10' 6"	10' 3"	10' 3"	9' 8"	8' 7½"	10' 3"	10' 0"	9' 6"	10' 3"
Height to highest point of roof, excluding current collector	12' 4"	11' 9"	14' 0"	15' 6"	14' 6"	14' 8"	13' 10"	13' 10"	14' 9"	12' 3"	12' 4"	12' 4"	12' 1"	14' 9"
Total weight (tons)	47	56	90	71.5	112	140	91	98	107	48.4	60	71	67	240
Weight on driving axles (tons)	47	56	90	71.5	112	89.3	68.8	75.4	78.2	38.7	60	50-44	67	196
Weight on pony axles (tons)	..	..	..	..	..	50.7	22.2	22.6	28.8	9.7	..	21-27	..	44
Total wheel-base	24' 6"	27' 0"	27' 6"	26' 0"	46' 0"	55' 11"	30' 10"	40' 6"	37.1'	26.9'	20'	27' 6"	26.2'	42' (one unit)
Total coupled wheel-base	..	..	..	..	..	7' 2"	..	..	24' 0"	15' 9"	20' 0"	12' 0"	26.2'	11' 0"
Fixed wheel-base	7' 6"	6' 6"	9' 6"	8' 8"	5' 0" and 6' 6"	7' 2"	8' 0"	8' 0"	14' 9"	7' 10½"	12' 7½"	12' 0"	15' 0"	11' 0"
Diameter of driving wheels	38"	36"	48"	46"	36"	72"	62"	63"	53.2"	42"	42"	64.1"	49½"	62"
Diameter of pony wheels	..	..	..	..	..	36"	33"	33"	33½"	28"	..	37.8"	..	30"
Distribution voltage	600 c.c.	550 c.c.	600/650 c.c.	2,400 c.c.	600/350 c.c.	650/750 c.c.	11,000 1 ph.	11,000 1 ph.	15,000 1 ph.	10,000 1 ph.	3,800 3 ph.	3,300 3 ph.	3,000 3 ph.	11,000 1 ph.
Frequency	..	..	..	..	..	..	25	25	15	16½	16½	16½	16	25
Type of motor	series	series	series	series	series	series	com- pensated series	com- pensated series	com- pensated series	com- pensated series	polyphase induction	polyphase induction	polyphase induction	polyphase induction

Normal operating voltage of motor	600	550	600/650	1,2000	600	660/750	220/300	275	420	280	3,300	3,300	3,000	725
Number of motors	4	4	4	4	8	2	4	8	2	2	2	2	2	8
Rated H.P. of each motor	200	60	300	300	330	1,500/2,000	240	168	1,250	300	1,000	1,300	550-850	410
System of transmission	single gearing	single gearing	twin gearing	twin gearing	direct	connecting-rod	direct	single gearing	single gearing and scotch yoke	single gearing and connecting rod	scotch yoke	scotch yoke	coupling rod	twin gearing and connecting rod
Gear ratio	3.36	3.28	4.37	4.83	..	..	..	4.18	2.23	4.47	..	..	..	4.78
Tractive-effort of locomotive corresponding to one-hour rating (lb.)	15,000	15,400	35,000	25,000	20,400	40,000	8,900	18,600	29,800	12,670	30,800	20,900	25,000-13,200	85,800-46,000
Tractive-effort of locomotive at 25 per cent. adhesion (lb.)	26,300	31,360	50,000	40,000	62,500	50,000	8,500	42,000	43,800	21,700	33,600	28,000	37,500	110,000
Speed of locomotive corresponding to one-hour rating (ml.p.h.)	19.5	8.6	12	15	48	36 (at 600 volts nominal field)	40.5	27.5	31	17.36	24.3	46.6	16.15-43.5	14-28
Number of jack-shafts . . . . .	..	..	..	..	..	2	..	..	2	1	..	..	..	4
Length of shortest coupling-rod . . . . .	..	..	..	..	..	5' 6"	..	..	4' 7.9"	3' 11 1/2"	..	5' 5"	5' 7"	4' 8"
System of control	B.T.-H. Type M	B.T.-H. Type M	G.E. Type M	G.E. Type M	G.E. Type M	W. electro-pneumatic	W. electro-pneumatic	W. electro-pneumatic	motor-operated drum controller	motor-operated drum controller	electro-pneumatic, 2-speed, cascade parallel	electro-pneumatic, 4-speed, cascade pole-changing	pneumatic, 4-speed, pole-changing	electro-pneumatic
Number of control notches	9	9	24	19	24	31	20	9	12	12	2	4	4	2
Builders of electrical equipment	B.T.-H.	B.T.-H.	G.E. Co.	G.E. Co.	G.E. Co.	Westing-house	Westing-house	Westing-house	Oerlikon	Oerlikon	Società Italiana Westing-house	Società Italiana Westing-house	Brown, Boveri	Westing-house
Builders of mechanical part of locomotive	Met. Rly. Carr. & Wagon Co.	Brush Co.	American Locomotive Co.			Pennsylvania R.R.	Baldwin Locomotive Works.	Baldwin Locomotive Works.	Swiss Locomotive Works	Swiss Locomotive Works	..	..	Swiss Locomotive Works	Baldwin Locomotive Works

* Continental class nomenclature. Initial capitals A, B, C, D, E denote respectively 1, 2, 3, 4, 5 coupled driving axles. Numerals placed before or after these letters denote the number of pony axles. The plus (+) sign shows the division of driving axles on separate trucks.

† Locomotives and rolling stock on the Rhaetian Railway are built to metre (3' 3 3/4") gauge.

CHAPTER XVIII

TRAIN RESISTANCE

TRAIN resistance is the term applied to the forces resisting the motion of a train when it is running at uniform speed * on a straight and level track. Under these conditions the whole of the energy output from the driving axles is expended in overcoming train resistance. Thus a portion is consumed in overcoming the friction internal to the rolling stock; another portion is consumed in overcoming the external resistances between the rolling stock and the track; and the remaining portion is consumed in overcoming air-resistance.

The **internal resistance** of the rolling stock is made up of friction at the journals, guides, bogies, buffers, &c.

The **external resistances** include rolling friction between the wheels and rails, flange friction between the wheels and rails, resistances resulting from the temporary deflection of the track due to the passage of the train over it.

The internal and external resistances together constitute the **mechanical resistance** component of train resistance. These resistances do not admit of detailed analysis on account of their varied and uncertain nature. For example, flange friction depends largely upon accidental conditions such as oscillation of the coaches, lateral wind pressure, &c., while the track resistance is influenced by the condition of the track, the strength of the rails, and the nature of the ballast.

It is probable that some of these resistances increase with the speed, while others may be unaffected or may even decrease with the speed. At low and moderate speeds (between 5 ml.p.h. and 40 ml.p.h.) we are probably correct in assuming that the mechanical resistance increases directly with the speed,† but at higher speeds there is evidence to show that this relation does not hold good. In fact the train-resistance tests ‡ carried out on the Marienfelde-Zossen experimental track indicate that, for the particular coaches experimented with, the mechanical resistance is practically constant between speeds of 90 and 125 ml.p.h. However, at these high speeds the train resistance consists principally of air resistance, and the mechanical resistance is only a small fraction of the total.

* See p. 20 for a discussion on the apparent train resistance during acceleration.

† This law does not hold good for the very low speeds incidental to starting, as the resistance under these conditions is very much greater than that at speeds above 4 to 5 ml.p.h.—due to increased track resistance and journal friction.

‡ See *Journal of the Institution of Electrical Engineers*, vol. 33, p. 894. Paper by Mr. Alexander Siemens on "High-Speed Electric Railway Experiments on the Marienfelde-Zossen Line."

The mechanical resistance is generally assumed to be proportional to the weight of the train, and, for a given class of rolling stock, this assumption is probably correct. It has been observed,* however, that to haul trains composed of heavy rolling stock requires less tractive-effort per ton of train weight, under the same conditions of speed, than similar trains composed of light coaches. A similar result has been obtained in certain tests with bogie freight wagons, where the tractive-effort per ton of train weight required to haul a train of loaded wagons was only 56 per cent. of that required to haul the same train of empty wagons over the same track under similar conditions of speed.† An explanation of this phenomenon is that the flange friction of a bogie truck is reduced by an increase of load; and this agrees with the facts connected with the running of bogie trucks.

The **air resistance** portion of train resistance is generally assumed to vary as the square of the velocity of the train, and therefore it requires careful consideration in high-speed work. The air resistance may be divided into two components, viz. one associated with the ends of the train and the other with the length of the train. The former includes the head resistance and the suction effect at the rear of train, while the latter includes the air friction on the sides, top, and underside of train, and is termed "skin friction."

The **head resistance** depends on the exposed surface at right angles to motion; it is largely influenced by the shape of the leading portion of the train and the direction and velocity of the wind. With trains hauled by locomotives the largest portion of the head resistance is encountered by the locomotive, but with electric trains operated with motor-coaches and trailers the whole of the head resistance is encountered by the leading coach. By suitably shaping the end of this coach it is possible to obtain a considerable reduction in head resistance.

The **suction resistance** at the rear of the train is also affected by the shape of the end coach, but as the magnitude of this resistance is only about one-tenth of the head resistance, the shape of this portion of the train is not so important as that of the opposite (or leading) end.

The manner in which air resistance is influenced by the contour of the front and rear portions of the train is shown by the curves of Fig. 349. These curves indicate the results obtained by the St. Louis Railway Test Commission ‡ on an experimental motor-coach fitted with vestibules of different forms, viz. (1) flat; (2) partially rounded (the standard type on U.S. interurban cars); (3) parabolic; (4) parabolic wedge, the relative shapes being shown in Fig. 350.

The **skin-resistance** component of the air resistance depends on the

* See a paper on "Train Resistance" by Mr. J. A. F. Aspinall (*Minutes of Proceedings of the Institution of Civil Engineers*, vol. 147, p. 155). This paper contains the results of elaborate tests carried out on the Lancashire and Yorkshire Railway.

† See *Railroad Gazette*, vol. 31, pp. 207, 262. Also a paper on "Predetermination of Train Resistance" by Professor C. A. Carus Wilson (*Minutes of Proceedings of the Institution of Civil Engineers*, vol. 171, p. 227).

‡ See *Report of Electric Railway Test Commission* (St. Louis), p. 534. The car on which the air resistance tests were conducted had the following dimensions: length over corner posts, 32 ft.; width 8 ft. 4 in.; height from side sills to top of roof, 9 ft. 5 in.; projected area of each vestibule (at right angles to motion), 96 sq. ft. The car-body was specially mounted on dynamometers, so that the total air resistance and the head resistance could be measured directly.

length of the train, the type of coaches, the nature of the external fittings, projections, &c. It is affected to some extent by side winds, but there is very little data available to indicate the effect of side winds or other conditions on the skin resistance. In the case of long trains skin resistance becomes an important item in the air resistance; and even for short trains it cannot be neglected, especially when the leading portion of the train is shaped to give the minimum head resistance.

As the air resistance depends entirely on the external configuration of the train, lightly-built coaches—such as the rolling stock used for the suburban services of some steam railways—will have practically the same air resistance as coaches, of much heavier construction, which form the rolling stock on the main lines of our large railways. But when

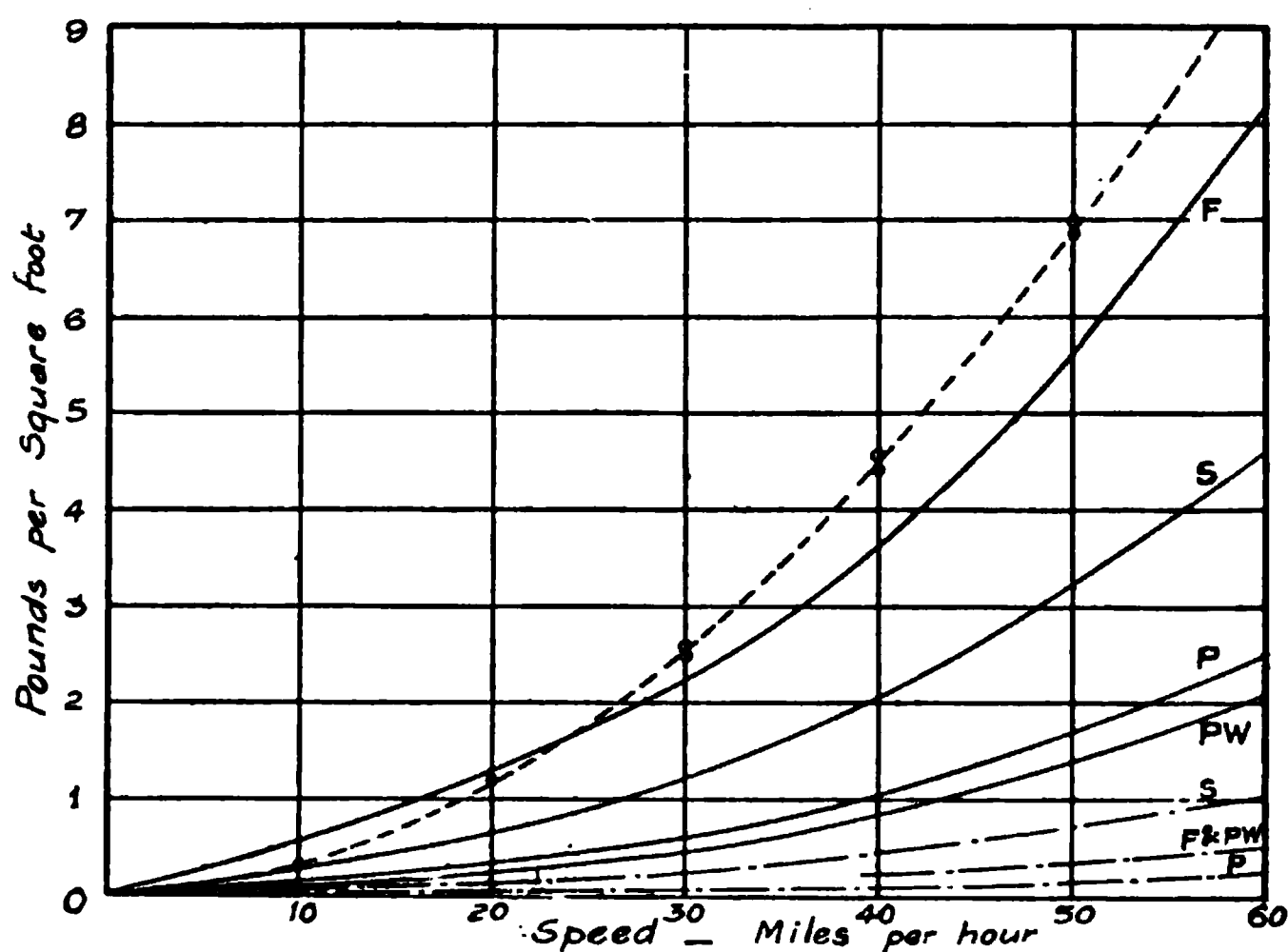


FIG. 349.—Air-resistance Curves for Motor-coach with various types of Vestibules: *F*, flat end; *S*, standard U.S.; *P*, parabolic; *PW*, parabolic wedge. NOTE.—Full lines show the head resistance; chain dotted lines show the suction resistance. The dotted curve is drawn through points calculated from equations: $p = 0.0028 V^2$ and $p = 0.003 V^2$.

the air resistance is expressed in terms of the train weight, the lighter coaches will appear to have the higher resistance.

Methods of Determining Train Resistance.—The methods of conducting train resistance tests with steam trains are: (1) by determining the draw-bar pull of the locomotive and the speed of the train under conditions of uniform speed; (2) by allowing the train to coast (without the locomotive), and obtaining an accurate record of the retardation.*

The first method requires a dynamometer-car, and has the disadvantage that only a portion of the head resistance is included in the dynamometer reading. This disadvantage is not apparent when considering

* The retardation can be determined directly by the Wimperis accelerometer (see p. 140), which is made with ranges suitable for train-resistance tests.

trains hauled by locomotives, as the largest portion of the head resistance is encountered by the locomotive, and would be included in the resistance of the locomotive. The train resistance is obtained from the product of the draw-bar pull and the speed, and in some dynamometer-cars this is recorded graphically by one instrument.*

The second method has the drawback (which is associated with all coasting tests on trains) that the whole of the head resistance is encountered by the leading coach, and therefore the retarding force on this coach is greater than that on the following coaches. Consequently there is a tendency for the coaches to crowd together, which produces greater oscillation and flange friction than when the couplings are tight. The train resistance is obtained from the retardation in the following manner:—

The force necessary to produce a retardation of 1 ml.p.h.p.s. on an

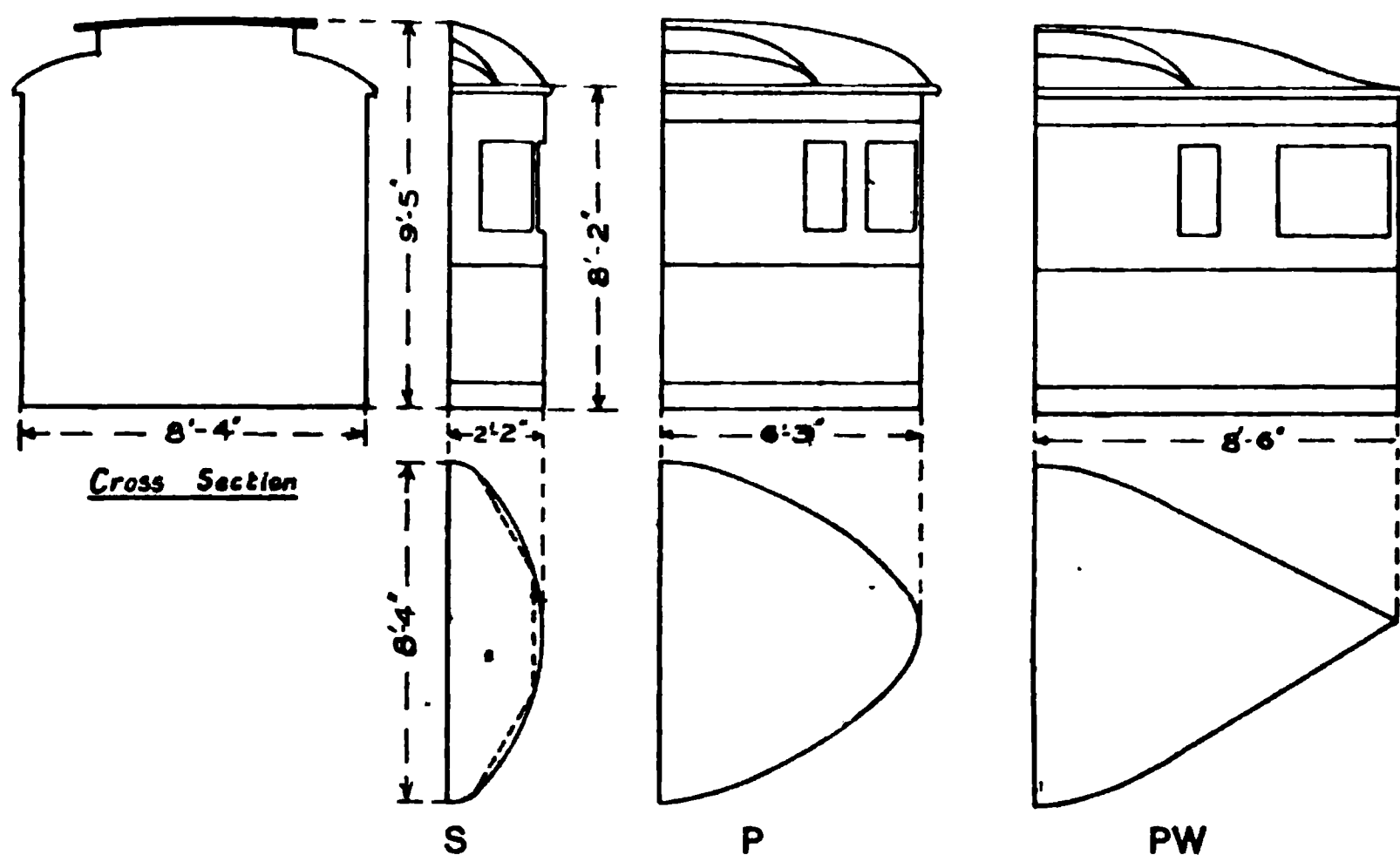


FIG. 350.—Types of Vestibule used for Air-resistance Tests of Fig. 349.

effective weight of 1 ton is 102 lb. (p. 18). Hence, if β is the retardation in ml.p.h.p.s., and W_e is the effective weight of the train, the total retarding force will be $102\beta W_e$ lb., which will be equal to the train resistance, provided that the train is on a level track. It is essential that the contour of the track be accurately known, as an "up" gradient of 1 in 1000 corresponds to a retarding force of $2\frac{1}{4}$ lb. per ton of train weight.

The effect of gradients can be eliminated by using an ergometer, by which instrument a record is obtained of the total work done against resistances other than gravity. The train resistance is then obtained by dividing the work done by the distance traversed.

With electric trains the total train resistance can be determined by observing the voltage and current input to the motors when the train is running at uniform speed. The tractive-effort and speed can then be

* See *Tramway and Railway World*, vol. 23, p. 16, for illustrations of instruments.

deduced from the characteristic curves of the motors: the tractive-effort will correspond to the train resistance, provided that the train is on the level and is not being accelerated.

With the usual motor equipment the free-running speed of the train occurs on the steep portion of the speed curve of the motor, so that a small error in reading the current may result in a relatively large error in the speed. Moreover, as free-running is approached very slowly with the full motor equipment, a long stretch of level track would be required in order to eliminate the above sources of error. This objection can be overcome by using a train with a small motor equipment. Thus, with several motors controlled on the multiple-unit system, the train can be accelerated, by the whole equipment, to approximately the speed required, and then a number of motors may be cut out, so that the train may be kept running at uniform speed.

The coasting method of determining train resistance may also be used with electric trains. In this case, however, the total resistance to motion includes not only the train resistance, but also the friction in the motors and gears, which, in trains equipped with several motors, may amount to a considerable percentage of the total resistance. The effect of the revolving parts (armatures, gears, and wheels) must be taken into account in deducing the train resistance from the observed retardation, as the stored energy in these parts may, in some cases, amount to over 10 per cent. of that for the whole train.

Train Resistance Formulæ.—In view of the large number of variables involved in train resistance, it is not surprising to find a large number of formulæ* of varied forms to express the law of variation of train resistance with speed. These formulæ, when applied to a given train, will be found to give widely divergent results. Hence train resistance formulæ must be used with discrimination, as, although each formula may be correct for the conditions under which it was derived, the probability of similar conditions for the tests of different investigators is very remote. Such items as the type of coach, the nature of the track, and the method of testing would be quite sufficient to cause large variations in the results.

In this country we are indebted to **Mr. J. A. F. Aspinall** for most of our data on train resistance. **Aspinall's tests** † were made with main-line oil-lubricated bogie coaches on the **Lancashire and Yorkshire Railway**, the dynamometer-car method being used. An attempt was made to use the coasting method, but the results obtained were so erratic that they were discarded. A very large number of tests were made with a train composed of five bogie coaches and a dynamometer-car. Tests were also made with trains composed of 10, 15, and 20 coaches. The results of the tests are represented in Fig. 351, and the following law for the train resistance between speeds of 10 and 80 ml.p.h. was deduced by Aspinall:—

$$r = 2.5 + \frac{V^3}{51 + 0.0278L} \quad \dots \dots \dots (33)$$

* A collection of formulæ will be found in the *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 147, pp. 189–192.

† Paper by Mr. J. A. F. Aspinall on "Train Resistance" (*Minutes of Proceedings of the Institution of Civil Engineers*, vol. 147, p. 155).

where r is the specific train resistance * in lb. per ton of train weight, V is the speed in miles per hour, and L is the length of the train in feet.

The train resistance at speeds below 10 ml.p.h. follows a different law. For instance, in the tests on the 5-coach train, the average resistance at starting was found to be 17 lb. per ton, which rapidly decreased to about 3 lb. per ton at a speed of 5 ml.p.h., and then increased slowly with increasing speed. The increased resistance at low speeds is shown in Fig. 351.

It should be noted that the above tests were made with coaches hauled by a steam locomotive, so that the formula only gives the head resistance for that part of the coach not shielded by the locomotive.

Aspinall also made tests to determine the magnitude of the head

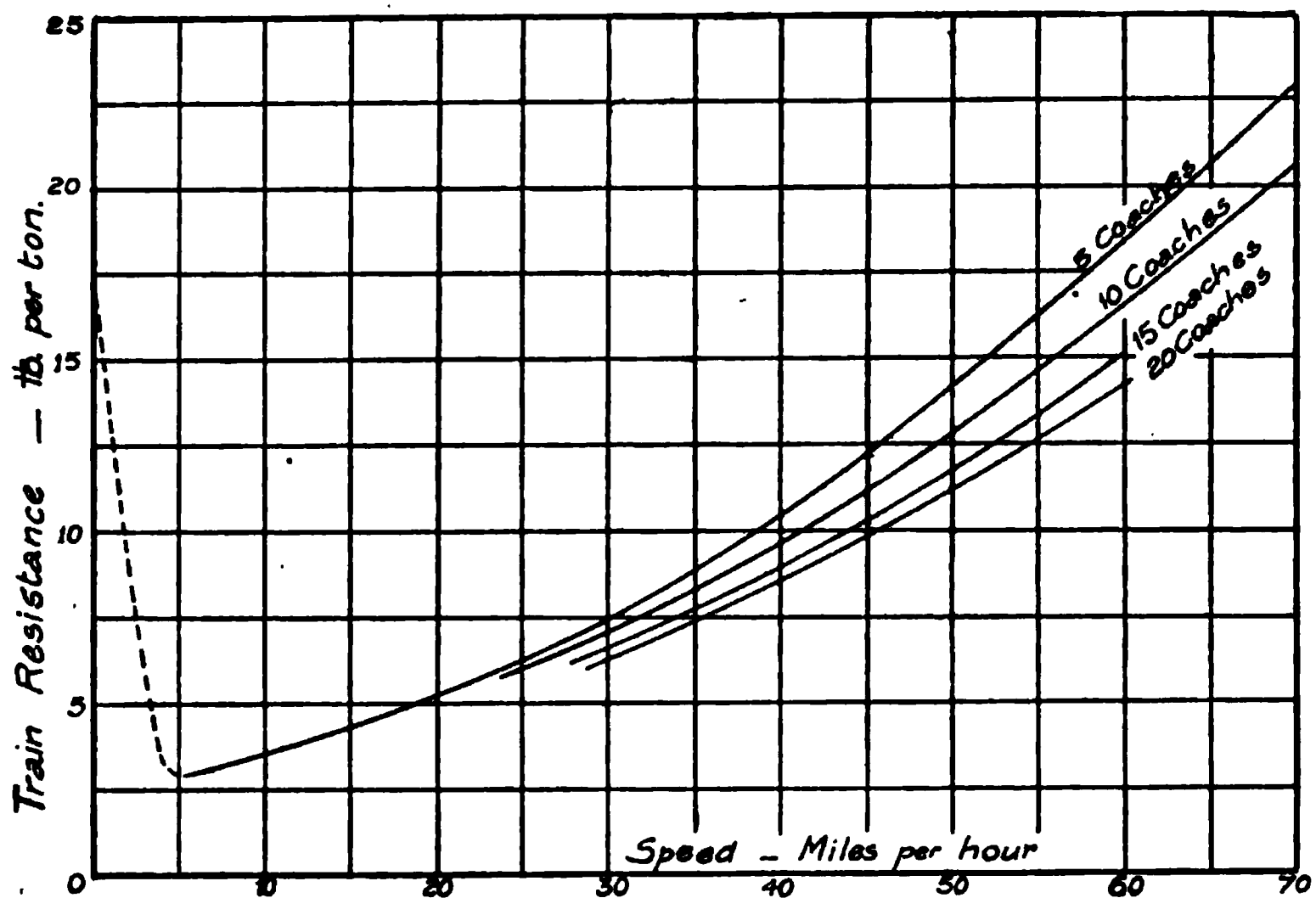


FIG. 351.—Results of Aspinall's Tests for Train Resistance.

resistance by measuring the air pressure on the exposed portion of the coach. The results obtained indicate that the air pressure p (expressed in lb. per square foot of exposed surface at right angles to the direction of motion) follows the law $p=0.003 V^2$, where V is the speed in ml.p.h. A similar result has been obtained in the Marienfelde-Zossen high speed tests, but in this case the coefficient was found to be 0.0028.

The results of these air-pressure measurements are represented by the dotted curve in Fig. 349. In comparing this curve with that given for the flat vestibule, it should be noted that the latter was derived by measuring the total pressure on the vestibule, whereas in the above tests an indirect method was used. It is probable that the lower results

* The customary method of expressing train resistance is in lb. per ton of train weight, which may be termed the "specific train resistance."

For moderate speeds this method provides a suitable means for comparing the results of tests and for estimating purposes. But, for high speeds, where the air resistance is the principal component of the train resistance, the above method is no longer suitable, since it is liable to lead to erroneous conclusions when applied to trains of different weights.

indicated by the St. Louis tests are due to a falling-off of the pressure at the edges of the vestibule.

General Equation for Train Resistance.—From a summary of the preceding discussion on the components of train resistance, we should expect the law of variation of resistance with speed to be of the form—

$$R=a+bV+cV^2;$$

where R is the total train resistance in lb., V is the speed of the train in m.p.h., and a , b , c are constants related to the particular train and track. In this equation the first two terms represent the mechanical resistances, while the last term represents the air resistance.

The author has examined the results of Aspinall's tests to ascertain if they conform to the law $R=a+bV+cV^2$. It was found that the curves closely approximated this law, and the following equations were obtained for the 5-, 10-, and 20-coach trains—

$$\begin{aligned} \text{5-coach train: } R &= 230 + 10.3V + 0.322V^2 \\ \text{10-coach train: } R &= 402 + 20.6V + 0.547V^2 \\ \text{20-coach train: } R &= 800 + 35.2V + 0.86V^2. \end{aligned}$$

Now, the last term in these equations represents the air resistance. Hence by estimating the head and suction resistances we can arrive at an approximate value for the skin resistance. Moreover, the value so obtained may be checked by the difference in the air resistances for trains of different lengths. Treating the tests on the 5-coach and 10-coach trains in this manner we obtain, for the skin resistance, an average value of $0.000035V^2$ lb. per square foot of longitudinal exposed surface.

For coaches with elliptical roofs, of the usual proportions on the main-line railways of this country, the longitudinal exposed surface (S) per coach is given approximately by

$$S \text{ (Square feet)} = 0.35LA,$$

where L is the length of the coach in feet and A is the transverse cross-section of the coach-body in square feet.

Hence, if the head resistance is taken at $0.0028V^2$ lb. per square foot of transverse exposed surface, the coefficient c in the general equation for train resistance becomes

$$\begin{aligned} c &= 0.0028kA\lambda + 0.0000122nLA \\ &= A(0.0028k\lambda + 0.0000122nL), \quad \dots \dots \dots (34) \end{aligned}$$

where k is a coefficient to include the effect of the shape of the end of the coach (see below), λ is the ratio $\frac{\text{exposed transverse surface}^*}{\text{cross-section of coach body}}$,

n is the number of coaches in the train, L is the length of each coach in feet, and A is the transverse cross-section of the coach-body in square feet. The following values, based on the curves of Fig. 349, may be taken for k .

Type of End of Coach (see Fig. 350).	k .
Flat	1.0
Partially rounded (Standard U.S. interurban cars)	0.65
Parabolic	0.3
Parabolic Wedge	0.28

* This term is introduced to include the shielding effect of the locomotive. For motor-coach trains $\lambda = 1.0$.

From the above equations for the resistance of 5-, 10-, and 20-coach trains we can obtain an approximate general expression for the total mechanical resistances. Thus the total mechanical resistances (in lb.) for a train of W tons—

$$= W\{1.8 + V(0.185 - 0.0393 \log W)\}$$

Hence, for trains consisting of trailer bogie coaches (main-line stock, with oil-lubricated journal boxes) running on good track, the train resistance may be estimated from the general formula:—*

$$R = W\{1.8 + V(0.185 - 0.0393 \log W)\} + AV^2(0.0028\lambda + 0.0000122nL), \quad (35)$$

$$\text{or } r = 1.8 + V(0.185 - 0.0393 \log W) + \frac{A}{W}V^2(0.0028\lambda + 0.0000122nL), \quad (36)$$

R being the total resistance in lb., and r the specific train resistance in lb. per ton of train weight.

This formula refers to *trains hauled by locomotives*, and is not suitable for electric motor-coach trains, as the resistance of these trains is considerably higher than that of trains operated with locomotives.

The increased resistance of motor-coach trains is manifested by the greater wear which these trains produce on the track rails,† and may be accounted for by (a) the heavy weight of bogie trucks with motors, (b) the unsprung-borne weight on the axles of the motor trucks, (c) the low centre of gravity of the motor-coaches, (d) the small diameter of the driving wheels. These conditions are not conducive to good riding qualities, and, in consequence, a large amount of flange friction and “nosing” (lateral oscillation) takes place, while the track is subjected to direct blows of considerably greater magnitude than those which occur with locomotive-hauled trains of trailer coaches.

As far as the author is aware, no tests have been made for the determination of the magnitude of these increased resistances. Tests have been made, however, on motor-coach trains,‡ but in all cases the coasting method has been adopted.

Now it is extremely important to remember that, for electric trains consisting of motor-coaches and trailers, there are *two train resistances* to be considered, viz. (1) the *true train resistance* when the power is “on”; (2) the *apparent train resistance* when the power is “off” and the train is coasting. In the latter case the motors are being driven by the train, and, in addition to the true train resistance, there is the friction losses in the motor-axle bearings, gears, armature bearings, brushes, and the windage loss in the motors. These losses are all attributed to the motors when the power is “on” (the characteristic curves of the motors being calculated for the output at the tread of driving wheels), and it would be impracticable to do otherwise, as the loss in the gearing will necessarily depend on the power being transmitted.

* It may be remarked here that all formulæ for train resistance refer to still-air conditions. In gusty weather the resistance will be greater, due to the increased air resistance.

† See *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 179, pp. 99, 143; vol. 197, p. 79. *Proceedings of the Institution of Mechanical Engineers* (1909), p. 438.

‡ See Mr. Aspinall's Presidential Address to The Institution of Mechanical Engineers (*Proceedings*, 1909, p. 473). Also *Journal of the Institution of Electrical Engineers*, vol. 50, p. 453; vol. 52, p. 446. *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 186, p. 46.

The additional retarding force due to motor and gear friction depends on the size and type of motor, the number of motors per train, the gear ratio, and the diameter of the driving wheels. In the case of trains operating on urban railways, where the motors are geared for a low free-running speed, the motor and gear friction may be of the order of from 4 to 5 lb. per ton of train weight. For suburban trains, operating at higher speeds, the motor and gear friction, at free-running speed, may be of the order of from 2 to 3 lb. per ton.

In order to derive a suitable formula for the resistance of motor-coach trains the author has analysed the curves which have been published (by Mr. Aspinall and Mr. O'Brien*) for the resistance of the

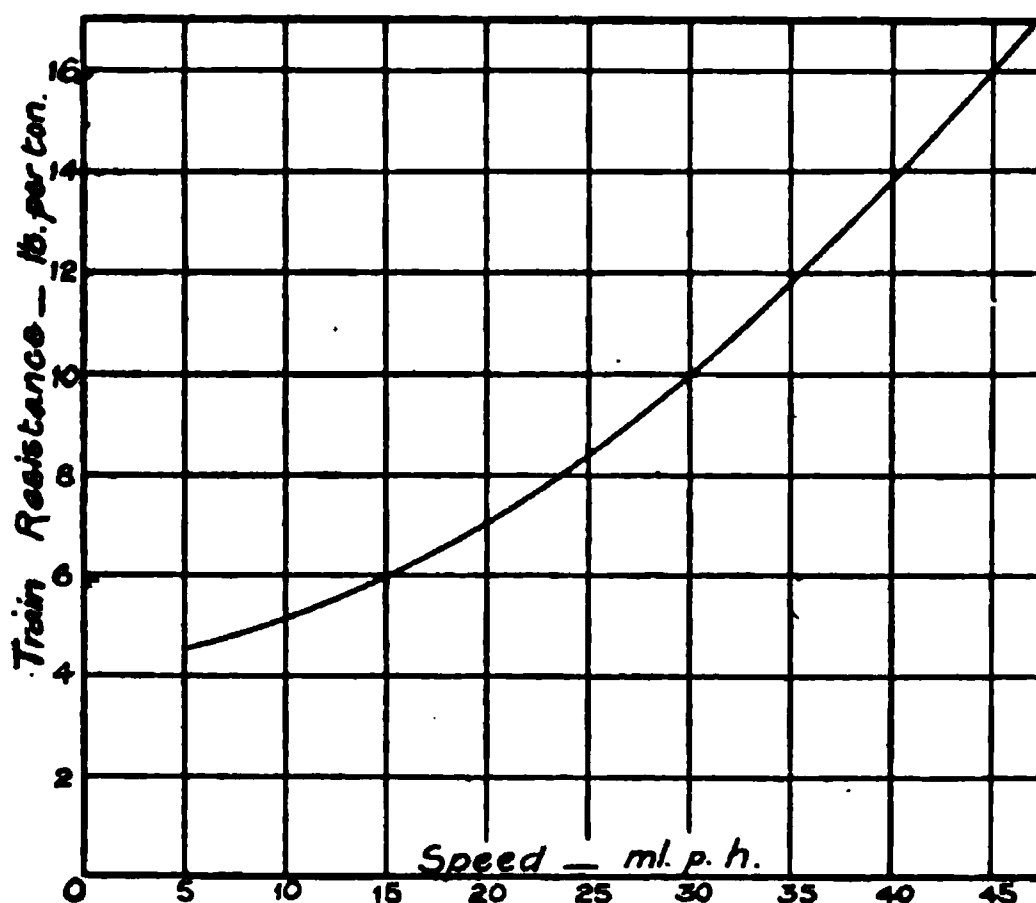


FIG. 352.—Corrected Curve for the Resistance of a Two-coach Electric Train.

electric trains on the Lancashire and Yorkshire Railway. Corrections have been applied for motor- and gear-friction and the effect of head winds. The corrected curve for the resistance of a two-coach train (consisting of one motor-coach and one trailer coach) is plotted in Fig. 352, and follows the law—

$$r = 4.1 + 0.055V + 0.0045V^2,$$

where r is the specific train resistance in lb. per ton of train weight, and V is the speed in ml.p.h.

Now a **general formula for the resistance of motor-coach trains** should discriminate between trains made up of motor-coaches only and those made up of motor-coaches and trailers. At the present time, however, there is not sufficient data available to enable this distinction to be made. Moreover, on some lines it is the general practice to operate one motor-coach with one or two trailer coaches as a "train-unit," the train being composed of one or more "train-units."

Therefore, a general equation, derived from Fig. 352, will enable the train resistance of motor-coach trains to be estimated with sufficient

* See *Proceedings of the Institution of Mechanical Engineers* (1909), p. 473; *Journal of the Institution of Electrical Engineers*, vol. 52, p. 446. The author is indebted to Mr. O'Brien for data of the latter tests.

accuracy, especially since the use of this class of train is restricted to urban and suburban services, in which the free-running period (if any) is only a small fraction of the total running period.

The general equation * derived from Fig. 352 follows the law—

$$R = W(4.1 + 0.055V) + AV^2(0.0028k + 0.0000122nL), \quad . \quad . \quad (37)$$

or
$$r = 4.1 + 0.055V + \frac{A}{W}V^2(0.0028k + 0.0000122nL), \quad . \quad . \quad (38)$$

where the symbols have the same significance as in previous equations.

Train resistance in tunnels.—The resistance of trains in tunnels is naturally higher than that of trains in the open on account of the increased air resistance. The effect of forced ventilation (such as is

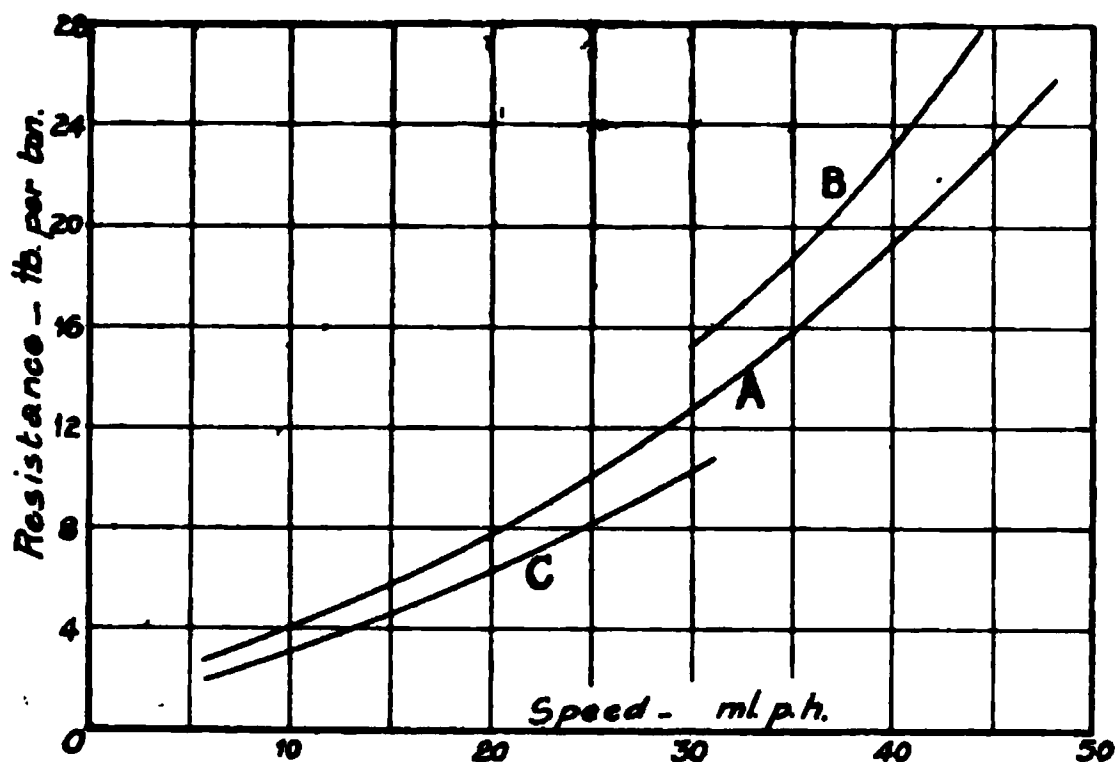


FIG. 353.—Resistance of 2-6-2 Electric Locomotive and Train in the Simplon Tunnel.

- A. Without forced ventilation in tunnel.
 B. { With forced ventilation { Motion of train opposite to direction of ventilating air.
 C. { in tunnel. { Motion of train in same direction as ventilating air.

required in very long tunnels) will also have a considerable influence on the train resistance. In this connection the curves of Fig. 353 † (which refer to the conditions obtaining in the **Simplon Tunnel**) are of interest. These curves give the resistance of a train and locomotive when running through the tunnel under different conditions of ventilation. The electric locomotive was of the 2-6-2 gearless type with side-rod drive (see Fig. 340). The weight of the locomotive was 62 tons; the transverse cross-section was 102 sq. ft.; while the cross-section of the tunnel was 253 sq. ft. The train (including the locomotive) weighed 327 tons, and was 666 ft. long.

In **tube railways**, where the clearance between the train and the tube is very small, the train resistance will be considerably affected by

* In these equations the value of k should be chosen from 15 per cent. to 20 per cent. higher than the values given on p. 418 to allow for the increased air resistance caused by the motors.

† From a paper by E. Thomann on "The New Electric Locomotives for the Simplon Tunnel." See *Genie Civil*, July 1909.

the increased air resistance, which in this case is practically all head resistance.

From tests carried out on the **Central London Railway**, the specific train resistance was found to follow the law $r = 6 + 0.5 \frac{V^2}{W}$.^{*} At a speed of 20 ml.p.h. the resistance of a 130-ton train (with seven cars) is 7.5 lb. per ton, while, in the open, the resistance at this speed—calculated from Aspinall's formula—is only 4.8 lb. per ton.

The **train resistance at curved track** is greater than that on straight track, due to greater flange friction, &c. The additional resistance will depend on the radius of the curve, the wheel-base of the trucks, and the end play between the wheel flanges and the rails. There is very little data available on the resistance at curved track; † this is probably due to the fact that to obtain accurate results a long stretch of track of uniform curvature is required.

A method adopted by American engineers for estimating the additional resistance at curves is to consider that each degree ‡ of curvature increases the train resistance 0.6 lb. per ton (2000 lb.) of train weight. In this country curves are usually expressed in terms of the radius (R), and if this is given in feet the additional train resistance will be

$$0.6 \times \frac{2240}{2000} \times 2 \sin^{-1} \frac{50}{R} = 1.35 \sin^{-1} \frac{50}{R} \text{ lb. per ton.}^{\S}$$

Track resistance of tramcars and railless cars.—The preceding formulæ all refer to the resistance of trains operating on railways

^{*} See *Electric Railway Engineering* (Parshall & Hobart), p. 9. Also *Proceedings of the Institution of Mechanical Engineers* (1912), p. 940. Mr. W. Casson (in a discussion on "The Dynamical Diagrams of a Train") states: "To show the effect of the increased air resistance in the tunnel . . . a single motor-car took just half the current and ran at the same speed as a train of seven cars, of which two were motor-cars, the speed being 27 ml.p.h. in each case. At this speed the tractive effort for the single car was 1000 lb., and that for the seven-car train was 2000 lb.

"From the Aspinall formula (33), the resistances of the car and the train would be, respectively, 7.2 and 6.65 lb. per ton, giving totals of 166 and 770 lb. There was, therefore, an additional total resistance, due to running in the tube, which was obviously independent of the weight of the train. . . . This additional resistance amounted to 834 lb. for the single car and 1230 lb. for the train.

[From these values we obtain 768 lb. for the head and suction resistances, 66 lb. for the skin friction of the single car, and 462 lb. for the skin friction of the seven-car train.]

"It was interesting to note that 768 lb. was about 8.5 lb. per square foot of cross-sectional area of the train. A water-gauge showed 1.5 in. difference of level between the back and front of the train, corresponding to 7.8 lb. per square foot."

† Some test results obtained on the City and South London Railway are given by Mr. McMahon in the *Proceedings of the Institution of Civil Engineers*, vol. 147, p. 215. The tests refer to a tube railway with a very light train and small wheels. The results indicate that a large increase in the train resistance occurs at sharp curves; for instance, on a curve of 540 feet radius the resistance at a speed of 13.5 ml.p.h. was found to be 22.6 lb. per ton, while the resistance at this speed on straight track was only 11.3 lb. per ton.

‡ In this system the curvature is given by the angle (in degrees) which a chord 100 ft. long subtends at the centre of curvature. Hence if θ is the curvature in degrees and R is the radius of the curve in feet, then $\sin \frac{\theta}{2} = \frac{50}{R}$, or $\theta = 2 \sin^{-1} \frac{50}{R}$.

§ It is interesting to note that the value given in the above footnote for the resistance of the City and South London trains on curved track corresponds to 1.06 lb. per ton per 1 degree of curvature.

where the track can be maintained in good condition. The resistance of tramcars operating through streets will be much higher than that of railway trains, on account of the different condition of the track and of differences in the construction of the cars and trucks.

The nature of the service on tramways and the low operating speeds, however, do not warrant an accurate estimation of the resistances to motion, and an average value of 25 lb. per ton may be assumed for general conditions.

With **railless cars** the resistance will be affected largely by the nature of the road surface and the class of tyres. On account of these indefinite conditions the values obtained for the resistance of motor vehicles can only be considered as a rough approximation to the average resistance. Thus the resistance of motor vehicles with pneumatic tyres on granite, asphalt, good macadam, or wood paving, has been found to be approximately 40 lb. per ton in dry weather and 50 lb. per ton in wet

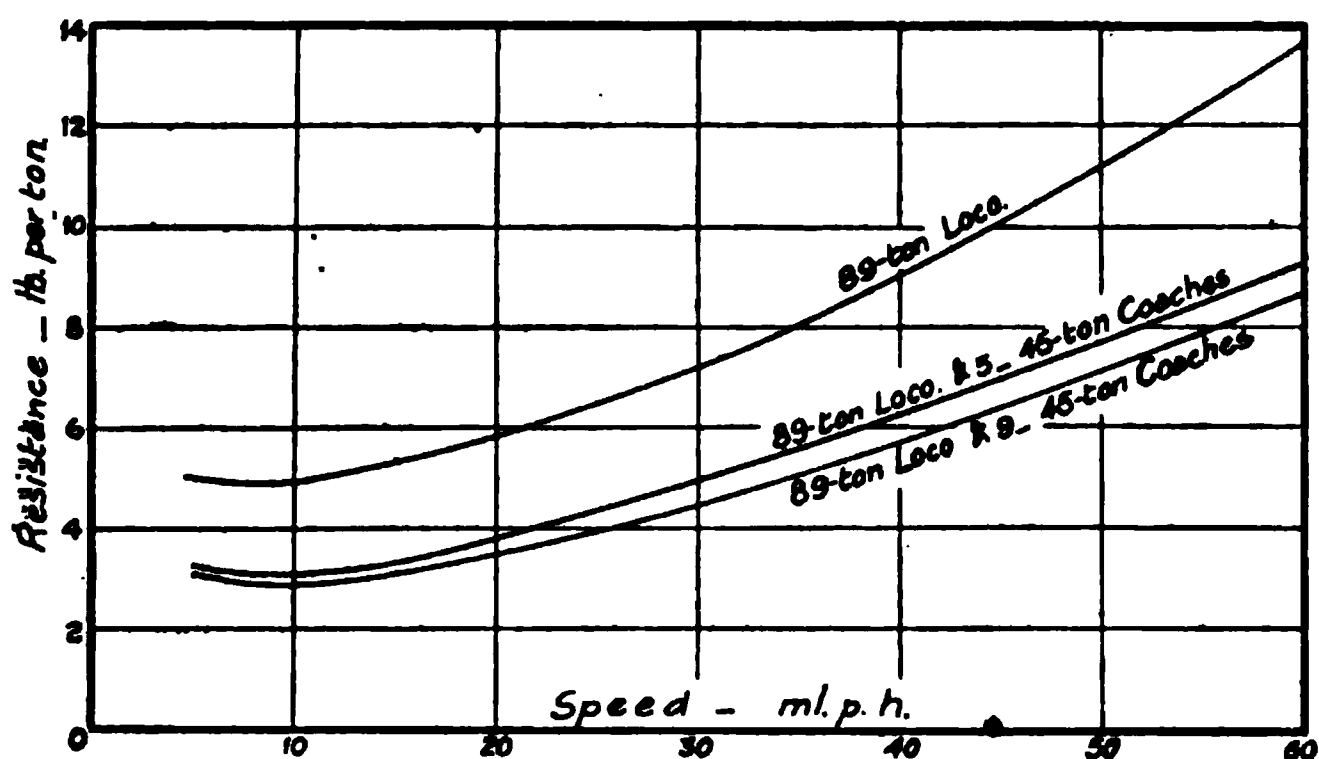


FIG. 354.—Resistance of "New York Central" Type of Gearless Locomotive.

weather. With solid rubber tyres values of 50 to 60 lb. per ton have been obtained in dry weather, and 80 lb. in wet weather.*

Resistance of Electric Locomotives.—The resistance of electric locomotives cannot be estimated with any degree of exactness on account of the large number of variables which enter into their design. Moreover, on account of the variety of designs it is impossible to derive formulæ suitable for general application. Therefore close approximations for the resistance of a particular type of locomotive can only be made when tests on a locomotive of a similar type are available.

Tests for the determination of the resistance of electric locomotives have been carried out in America and on the Continent. A large number of tests were made on the original 89-ton gearless locomotives for the **New York Central Railroad**.

The average resistance of the locomotive, calculated from the test

* See *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 159, p. 14 (paper by Col. R. E. Crompton on "Modern Motor Vehicles"); vol. 198, p. 24 (paper by Mr. T. G. Gribble on "Comparative Economies of Tramways and Railless Electric Traction"). The latter paper contains curves and data of the resistance of tramcars and railless cars.

results, is shown in Fig. 354, together with curves of the combined resistance of the locomotive and train.

The locomotives have four driving axles and two pony axles, the principal dimensions being given below :—

Length of cab	34 ft. 0 in.
Width of cab	10 „ 0 „
Height of roof above rails	13 „ 9 „
Height of bottom of side sills above rails	5 „ 0 „
Distance between centres of pony axles	27 „ 0 „
Distance between centres of driving axles	4 „ 4 „
Total weight on each driving axle	16.7 tons.
Dead weight per driving axle	5½ „

The resistance of the 102-ton **geared freight locomotives** in service on the **Cascade Tunnel** has been found to be 1500 lb.* (or 14.7 lb. per ton) at the normal speed (15 ml.p.h.) of the locomotives. These locomotives are of the double-truck type, and are equipped with four three-phase 475-H.P. motors, which drive 60-in. wheels through twin gearing of ratio 4.26:1. The cab is of the box type, with elliptical roof and practically flat ends, the principal dimensions being :—

Length of cab	40 ft. 2 in.
Width of cab	10 „ 0 „
Height of roof above rails	12 „ 8 „
Height of bottom of side sills above rails	4 „ 8 „
Wheel-base of trucks	11 „ 0 „
Distance between truck centres	20 „ 9 „
Total weight per axle	25.7 tons.
Dead weight per axle	8.26 „

In both of the above locomotives the motors are located on the trucks and in consequence the centre of gravity is low, while the dead weight per axle is fairly large. It will be interesting, therefore, to consider the resistance of a **gearless locomotive, with a side-rod drive**, in which the motors are mounted on the locomotive framing, so that the dead weight per axle is only that of the wheels, axle, and coupling rods. The resistance of a locomotive of this type is shown in Fig. 355.† The locomotive on which the tests were made was built by Ganz & Co. for the Valtellina line of the **Italian State Railways**. The total weight of the locomotive is 61 tons, of which 41 tons is carried on the three driving axles, and the remaining 20 tons on two pony axles. The driving wheels are 59 in. in diameter, and are coupled together by coupling-rods, the central wheels on each side being driven from the (two) motors by means of scotch yokes. The cab is constructed with sloping ends, the end faces of the central

* See paper on “The Electric System of the Great Northern Railway Co. at Cascade Tunnel,” by Dr. Cary T. Hutchinson (*Transactions of the American Institute of Electrical Engineers*, vol. 28, p. 1308). The resistance given above was determined by towing the locomotive, and, therefore, it includes the motor- and gear-friction.

† From a paper by F. Koromzay on “The New Electric Locomotives of the Valtellina Railway” (published in the *Revue Generale des Chemins de fer*, March, 1905).

portion being shaped to include an angle of approximately 100 degrees, for the purpose of providing an extended look-out and of diminishing

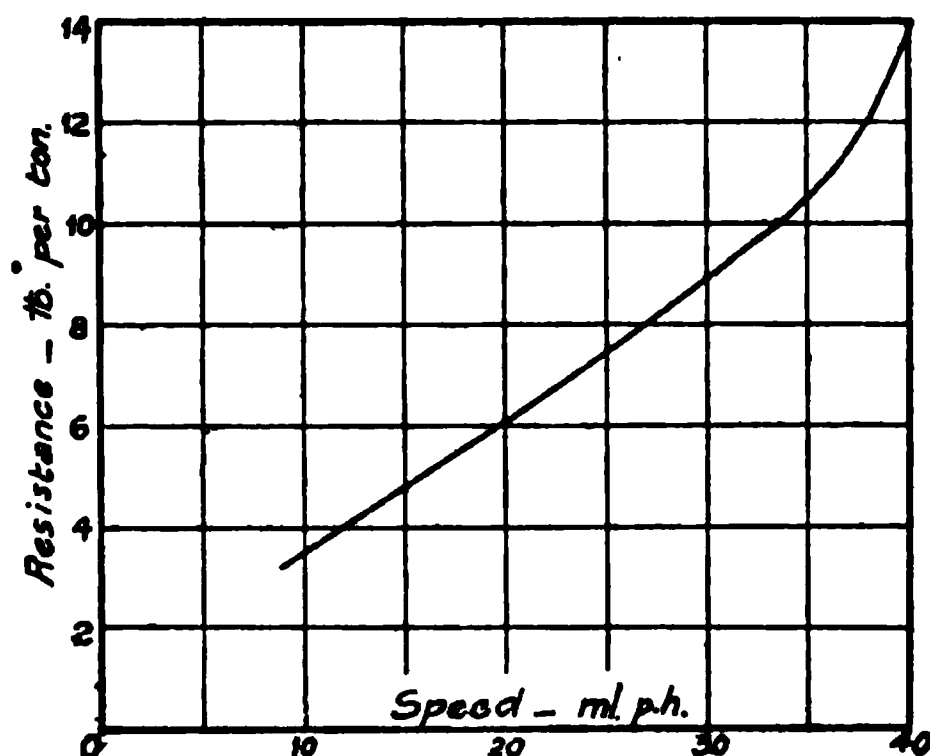


FIG. 355.—Resistance of 61-ton, 2-6-2 Gearless Locomotive with Side-rod (scotch-yoke) Drive.

the air resistance. The principal dimensions of the locomotive are given below :—

Total length of locomotive framing	34 ft. 5 in.
Width of locomotive framing	9 „ 6 „
Height of footplate above rails	5 „ 1 „
Length of body (overall)	31 „ 4 „
Length of central cab	20 „ 0 „
Width of central cab	9 „ 4 „
Width of sloping ends	7 „ 4 „
Height of roof above rails	12 „ 0 „
Height of sloping ends above footplate (max.)	3 „ 1 „
Height of sloping ends above footplate (min.)	2 „ 0 „
Total wheel-base (centres of pony axles)	31 „ 1.5 in.
Fixed wheel-base (i.e. twice distance between centres of driving axles)	15 „ 4.8 „

CHAPTER XIX

THE CALCULATION OF SPEED-TIME CURVES AND ENERGY CONSUMPTION FOR ELECTRIC TRAINS

PART I.—SPEED-TIME CURVES

THE importance of the speed-time curve in electric railway engineering has been considered in Chapter II. Although the simplified speed-time curve discussed in that chapter is convenient for preliminary calculations, it does not correspond to the actual operating conditions. Moreover, an accurate speed-time curve is required for energy calculations.

The calculations for the speed-time curve and the energy consumption are usually carried through together, since certain quantities—*e.g.* the current and the time—are common to both calculations. However, to simplify matters, we shall only consider the calculation of speed-time curves at present.

For the calculation of the speed-time curve we require :—

- (1) Complete information of the train service.
- (2) A survey of the route, showing the gradients, curves, stations, &c.
- (3) Sufficient particulars of the rolling stock and electrical equipment to enable the train resistance to be estimated and the effective weight to be computed.

- (4) The characteristic curves of the motors.

The method of calculating the speed-time curve involves only the application of elementary mechanics, the chief feature of the method being the adoption of the speed as the independent variable. The time intervals corresponding to certain increments of the speed are therefore obtained indirectly from the acceleration. The process is essentially a *point-to-point* one, and the accuracy of any point is governed by the accuracy with which the preceding points have been obtained.

The method of procedure is best illustrated by working through an example.

Thus, consider that a service of 175-ton motor-coach trains has to be run at a schedule speed of 16 ml.p.h. over a straight and level track for which the average distance between the stations is 2560 feet.* There is a stop of 20 seconds at each station.

The trains are composed of two motor-coaches, weighing 42·5 tons

* The schedule speed, average distance between stations, and duration of stop in this example correspond to the average service conditions on the "Inner Circle" portion of the Metropolitan District Railway, London.

each (without passengers), and four trailer coaches, weighing 22.5 tons each (without passengers), the total seating capacity of a six-coach train being 324. Each coach-body has a length of 52 ft., a maximum width of 8 ft. 9 in., and a transverse cross-section of 87.5 sq. ft. The height of the bottom of the side-sills above the rails is 2 ft. 11 in. Each coach is mounted on two four-wheel bogie trucks with 36-in. wheels, and each truck of the motor-coaches is equipped with two 150-H.P., 600-volt, continuous-current geared motors, which are controlled on the series-parallel system. The characteristic curves of the motors are given in Fig. 32 (p. 49). These curves have been calculated for the gear-ratio (3.5 : 1) and the size of driving wheels (36 in.) adopted on the above trains.

The armature of each motor is 18 in. in diameter and weighs 1500 lb. The average rate of braking is 2 ml.p.h.p.s., while the average accelerating current is 225 amperes per motor.

First, we must calculate the **effective weight of the train**. Considering the train to be loaded with its full complement of (seated) passengers, the total dead weight is $(175 + \frac{324}{16} \times 140 =) 195$ tons.

Hence, allowing 900 lb. for each wheel and substituting in equation (7), we obtain the effective weight (W_e) as—

$$W_e = 195 + 1.2 \times 24 \times \frac{900}{2240} + 0.49 \times 8 \times \frac{1500}{2240} \times 3.5^2 \times \left(\frac{9}{18}\right)^2 = 214.6 \text{ tons}$$

(i.e. 10 per cent. greater than the dead weight).

Second, we must obtain the **train resistance**. Now the transverse cross-section of the coaches is 78.5 sq. ft., and the motors increase this by about 11.5 sq. ft. Therefore, allowing for the chamfered ends of the coaches, the coefficient k in equation (34) may be taken at

$$\left(0.9 \times \frac{78.5 + 11.5}{78.5} =\right) 1.05.$$

Hence, from equation (38), we obtain for the specific train resistance the equation—

$$\begin{aligned} r &= 4.1 + 0.055V + \frac{78.5}{195} V^2 (0.0028 \times 1.05 + 0.0000122 \times 6 \times 52) \\ &= 4.1 + 0.055V + 0.00272V^2. \end{aligned}$$

Substituting various values for V , we obtain the following values for the train resistance :—

Speed, ml.p.h. (V)	10	15	20	25	30	35
Specific train resistance, lb. per ton (r)	4.92	5.53	6.3	7.2	8.2	9.34

The **apparent train resistance** during coasting will be greater than the above values, on account of the motor friction and gear losses. For the class of equipment under consideration the following values are representative of the friction and gear losses per motor :—

Armature speed, r.p.m.	250	500	750	1000	1150
Friction and gear loss, kw.	1.3	3.0	5.1	7.4	8.9

* The average weight of each passenger may be assumed to be 140 lb. Consequently 16 passengers will weigh 1 ton.

Rearranging these values to correspond to the retarding force per motor, we obtain :—*

Speed of train (ml.p.h.)	10	15	20	25	30	35
Retarding force per motor (lb.)	87.5	98	107	114	121	126.5

Hence the apparent train resistance during coasting is obtained by adding this additional retarding force to the true train resistance. The steps in the process are shown below :—

Speed of train (ml.p.h.)	10	15	20	25	30	35
Specific train resistance (r-lb. per ton)	4.92	5.53	6.3	7.2	8.2	9.34
Total train resistance (195 r-lb.)	960	1070	1230	1405	1600	1820
Retarding force due to 8 motors (lb.)	700	784	865	911	967	1010
Total retarding force (lb.)	1660	1854	2095	2316	2567	2830
Apparent train resistance (lb. per ton) or retarding force per ton (lb.)	8.5	9.5	10.75	11.88	13.15	14.5

The train resistance and the apparent train resistance during coasting are plotted in Fig. 356.

Third, we have to determine the tractive-effort available for

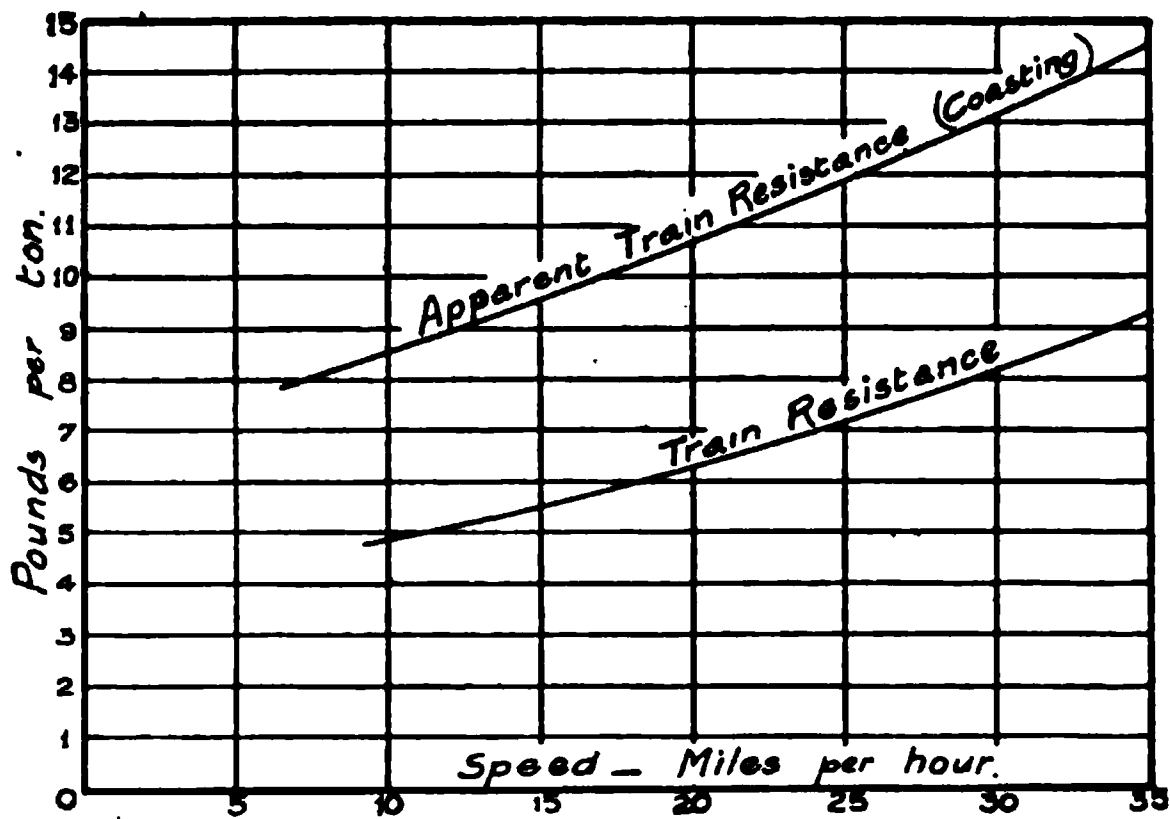


FIG. 356.—Train Resistance and apparent Train Resistance of Six-coach, 195-ton Electric Train.

acceleration at various speeds when the motors are running in parallel at normal voltage. This is readily obtained from the characteristic

* The method of converting the loss into retarding force is as follows. With a gear ratio of 3.5:1 and 36-in. wheels, the relation between the armature speed (r.p.m.) and the train speed (ml.p.h.) is—

$$\text{ml.p.h.} = \frac{\text{r.p.m.}}{3.5} \times \frac{60}{5280} \times 3\pi = \frac{\text{r.p.m.}}{32.65} .$$

Hence the retarding force (in lb.) corresponding to the gear and friction losses (in kw.) at this speed is

$$(\text{lb.}) = \frac{\text{kw.}}{\text{ml.p.h.}} \times \frac{33,000 \times 60}{0.746 \times 5280} = 503 \frac{\text{kw.}}{\text{ml.h.p.}} = 16,440 \frac{\text{kw.}}{\text{r.p.m.}} .$$

curves of the motor by deducting the train resistance from the tractive-effort curve. Instead of deducting the total train resistance from the total tractive-effort of the eight motors, we deduct one-eighth of the total train resistance from the tractive-effort of one motor, and thus obtain the accelerating force per motor, as shown in Fig. 357. By considering this force to act upon one-eighth of the mass of the train, we shall obtain the same conditions as if the total accelerating force of the eight motors acted upon the whole mass of the train.

We have now all the data necessary for the calculation of the speed-time curve.

I. Consider the **period of initial acceleration**. During this period the starting resistance is cut out to maintain the average accelerating current practically constant at 225 amperes per motor. When all resistance has been cut out in the parallel combination of the motors, the speed of the train (assuming normal voltage) will be 16.8 ml.p.h. (See speed curve, Fig. 32.) The mean train resistance during this period will be much greater than that corresponding to the average speed, and we shall, therefore, assume an average value of 8 lb. per ton.

Hence the average tractive-effort available for acceleration—

$$= 3500 - \frac{1}{8} \times 195 \times 8 = 3500 - 24.35 \times 8 = 3305 \text{ lb.}$$

(3500 is the tractive-effort, from Fig. 32, corresponding to a current of 225 amperes.)

Now this force acts upon one-eighth of the effective weight of the train, i.e. ($\frac{1}{8} \times 214.6 =$) 26.8 tons.

$$\text{Therefore the mean acceleration} = \frac{3305}{26.8 \times 102} = 1.21 \text{ ml.p.h.p.s.}$$

$$\text{Duration of accelerating period} = \frac{16.8}{1.21} = 13.9 \text{ seconds.}$$

$$\begin{aligned} \text{Distance run during this period} &= \frac{16.8}{2} \times \frac{13.9}{3600} \times 5280 \\ &= \frac{1}{2} \times 16.8 \times 13.9 \times 1.467 \\ &= 170 \text{ ft.} \end{aligned}$$

II. **Period of speed-curve running.**—We now select a series of increments of the speed, and calculate the mean acceleration for each interval, after which the time and distance are readily obtained.

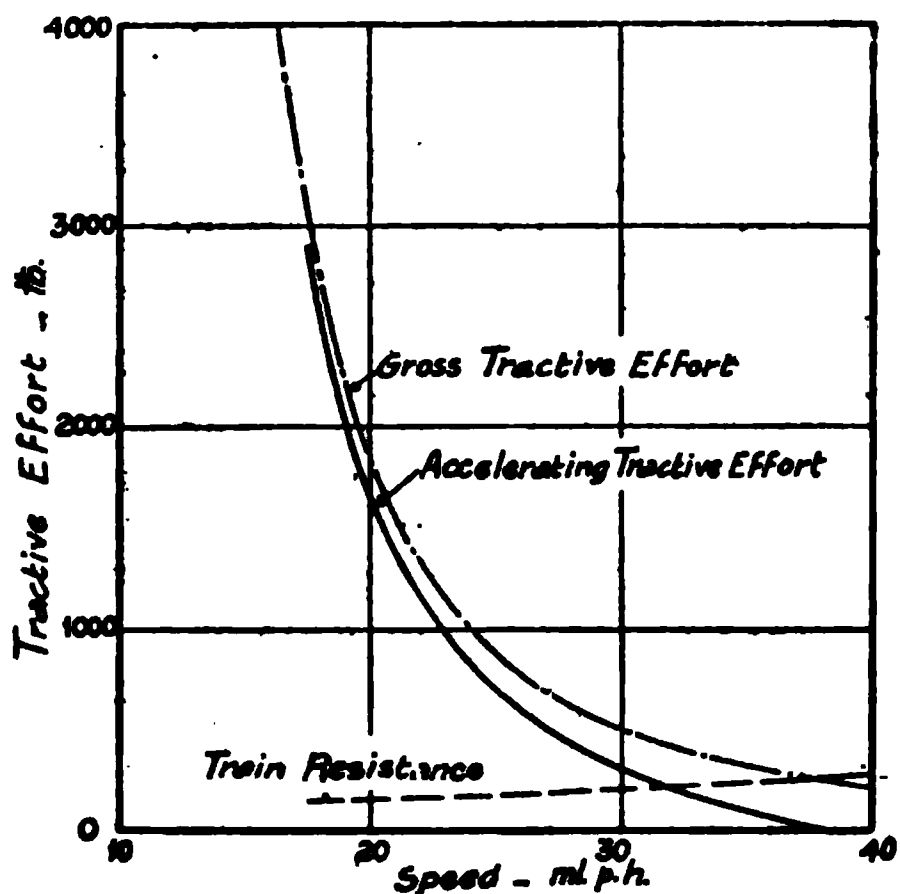


FIG. 357.—Curve connecting Speed and accelerating Tractive-effort per Motor for Six-coach Train.

Thus, consider the increment from 16·8 ml.p.h. to 19 ml.p.h. The mean accelerating tractive-effort (from Fig. 357),

$=\frac{1}{2}(3305+2090)=2697\text{ lb.},$

and the mean acceleration

$=\frac{2697}{26\cdot8\times102}=\frac{2697}{2735}=0\cdot987\text{ ml.p.h.p.s.}$

Time of interval

$=\frac{19-16\cdot8}{0\cdot987}=2\cdot23\text{ seconds.}$

Total time from start

$=13\cdot9+2\cdot23=16\cdot13\text{ seconds.}$

Distance run during interval

$=\frac{16\cdot8+19}{2}\times\frac{2\cdot23}{3600}\times5280$
 $=17\cdot9\times2\cdot23\times1\cdot467$
 $=58\cdot6\text{ ft.}$

Total distance from start

$=171+58\cdot6=229\cdot6\text{ ft.}$

We can repeat this process until the free-running speed (38·5 ml.p.h.) is reached, the free-running speed being obtained directly from Fig. 357. The results of these calculations are given in Table XIV.

TABLE XIV

CALCULATION OF SPEED-TIME CURVE FROM START TO FREE RUNNING FOR RUN ON LEVEL TRACK.

Speed.	Net Tractive-Effort.	Speed Increment.	Mean Accelerating Tractive-Effort.	Mean Acceleration.	Time Increment.	Time from Start.	Mean Speed.	Distance Increment.	Total Distance.
ml.p.h.	lb.	ml.p.h.	lb.	ml.p.h.p.s.	sec.	sec.	ml.p.h.	ft.	ft.
0	3305					0			0
16·8	3305	16·8	3305	1·21	13·9	13·9	8·4	171	171
19	2090	2·2	2697	0·987	2·23	16·13	17·9	58·6	230
21	1370	2·0	1730	0·633	3·16	19·29	20	92·7	322
22·5	1050	1·5	1210	0·433	3·39	22·68	21·75	108·1	430
25	710	2·5	880	0·322	7·76	30·44	23·75	270	700
27·5	490	2·5	600	0·219	11·38	41·82	26·25	438	1138
30	330	2·5	410	0·15	16·66	58·5	28·75	702	1840
35	105	5	218	0·08	62·8	121·3	32·5	2990	4830
38·5	0	3·5	52·5	0·0192	182·2	303·5	36·75	9810	14640

In the case of short runs, however, we seldom reach free-running speed. It is advisable, therefore, to plot the speed-time and distance-time curves after a few points have been calculated.

Now, since the schedule speed is 16 ml.p.h., the running time, for a distance of 2560 ft., will be $\left(\frac{2560 \times 3600}{5280 \times 16} - 20 =\right) 89$ seconds.

The accelerating and braking portions of the speed-time curve can now be drawn, and are represented in Fig. 358 by OA and DE respectively, OD representing the running time—89 seconds. DE , of course, makes an angle of $(-\tan^{-1} 2)$ with the time axis.

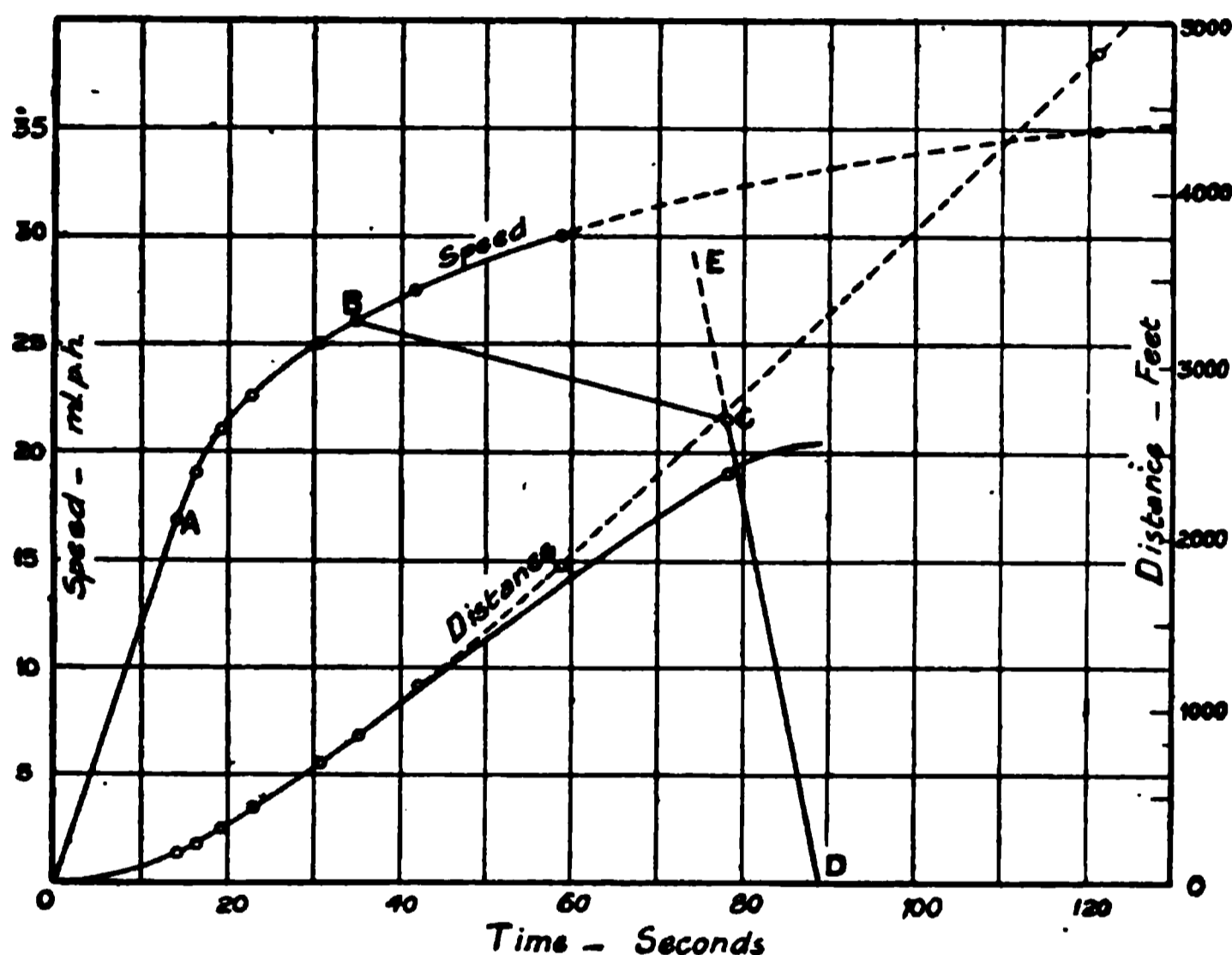


FIG. 358.—Speed-time Curve for Motor-coach Train (2560 ft. run on level track at 16 ml.p.h. schedule speed).

The points at which the power must be cut off and the brakes applied must now be determined. We know that the area of the speed-time diagram must represent the distance travelled during the running time—in the present case 2560 ft. Hence the coasting line BC (Fig. 358) must be drawn so that the area $OBCD$ represents 2560 ft., while the inclination of BC to the time axis must correspond to the mean retardation during the coasting period. It is apparent that this must be accomplished by a process of trial and error. With some experience, however, the correct position can usually be obtained on either the first or the second trial.

For instance, suppose we cut off power at 35 seconds when the speed is 26.1 ml.p.h. The distance travelled during this time is 875 ft., so that the train must coast for a certain period before the brakes are applied. In order to obtain the duration of the coasting period we must know the retardation. This can be obtained when the train resistance is known. Hence it is necessary to assume a value for the average

speed during the coasting period in order to obtain an appropriate value for the train resistance. In the present case we will assume the average speed as 24 ml.p.h., which corresponds to an apparent train resistance of 11.6 lb. per ton.*

Hence the retardation $= \frac{11.6 \times 24.35}{102 \times 26.8} = 0.103$ ml.p.h.p.s. The coasting line BC (Fig. 358) is now drawn on the curve-sheet, and the intersection of this line with the braking line gives us the point at which the brakes must be applied.† This point is found to be at 78.2 seconds, when the speed is 21.6 ml.p.h. Before proceeding further it is necessary to check our assumption of the average speed for the coasting period. This is $\{\frac{1}{2}(26.1 + 21.6)\} = 23.85$ ml.p.h., so that the value obtained above for the retardation will be substantially correct.

If the area of the diagram $OBCD$ be determined by a planimeter, it will be found to represent 2555 ft., which is sufficiently near the actual distance (2560 ft.) of the run to justify the correctness of our trial.

The alternative method of ascertaining whether or not the point of cut-off has been chosen correctly is to determine the distances by calculation, as follows:—

The time of the coasting period $= 78.2 - 35 = 43.2$ seconds,
 and the time of the braking period $= 89 - 78.2 = 10.8$ seconds.
 Hence the distance run during coasting $= 23.85 \times 43.2 \times 1.467 = 1510$ ft.,
 and the distance run during braking $= \frac{1}{2} \times 21.6 \times 10.8 \times 1.467 = 170$ ft.

The total distance run is, therefore, $875 + 1510 + 170 = 2555$ ft.

The complete speed-time curve together with the distance-time curve is shown in Fig. 358.

Effect of gradients and curves.—In practice we are not generally favoured with ideal track conditions—as assumed in the above example—but we have curves and gradients of varying amounts. When consider-

* The mean train resistance during coasting is slightly greater than the train resistance at the mean coasting speed, but the conditions of operation and other variable features do not warrant a closer estimation than that given above.

† The point of application of the brakes may be ascertained analytically by obtaining the co-ordinates of the point of intersection of the coasting and braking lines. Thus the equations of the coasting and braking lines are, respectively, given by

$$V' = U_1 - \beta_c t' \quad \dots \dots \dots (39)$$

$$\text{and} \quad V'' = U_2 - \beta t'' \quad \dots \dots \dots (40)$$

where V' , V'' , denote the speeds at times t' , t'' respectively; β_c , β denote the respective retardations during coasting and braking; U_1 and U_2 denote the hypothetical speeds at zero time (i.e. the intercepts on the vertical axis). If V''' , t''' denote the co-ordinates of the point of intersection of the coasting and braking lines, then $V''' = U_1 - \beta_c t''' = U_2 - \beta t'''$;

$$\text{whence} \quad t''' = \frac{U_2 - U_1}{\beta - \beta_c} \quad \dots \dots \dots (41)$$

V''' is, of course, obtained by substitution.

Applying this method to the above example we obtain the values of U_1 and U_2 by substituting known values for V' , V'' , t' , t'' . Thus, at the point of cut-off, $V' = 26.1$, $t' = 35$; while at the end of the braking period $V'' = 0$, $t'' = 89$. Hence, adopting the above value for the retardation during coasting, we obtain $U_1 = 26.1 + 0.103 \times 35 = 29.7$; $U_2 = 0 + 2 \times 89 = 178$. Therefore,

$$t''' = \frac{178 - 29.7}{2 - 0.103} = 78.2 \text{ sec., while } V''' = 178 - 2 \times 78.2 = 21.6 \text{ ml.p.h.}$$

ing the electrification of a particular railway, the energy consumption must be calculated for each section of the route before an accurate value of the average energy consumption over the whole route can be obtained. Hence it will be necessary to determine the speed-time curves for the actual track conditions, and if there are numerous gradients and curves the calculation by the above method will usually consume much time and patience. The effect of the gradients and curves on the train resistance can readily be allowed for, but the time of running on the various gradients and curves must be determined by trial. An example—representing typical conditions on a suburban railway—will best illustrate the method of procedure.

Suppose the above 175-ton motor-coach train has to operate over a section 4800 ft. long at a schedule speed of 20 ml.p.h. with a stop of 20 seconds at the station. The profile of the section is shown in Fig. 359, and the speed-time curve will be calculated for the direction

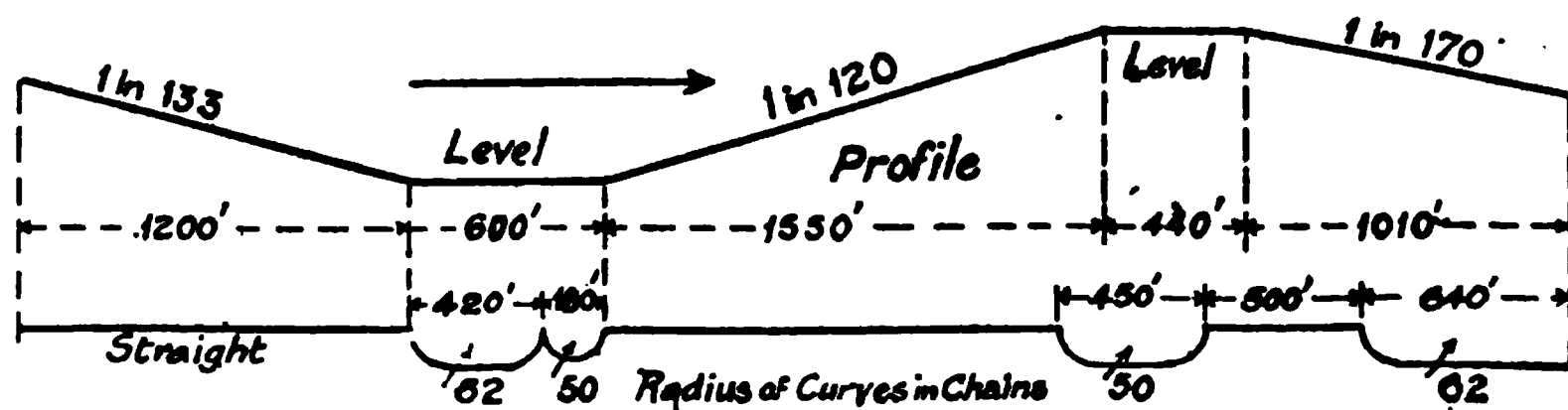


FIG. 359.—Profile of Track for Speed-time Curve in Fig. 360.

of running indicated by the arrow. The mean accelerating current is 225 amperes (as above), and the average rate of braking on level track is 2.0 ml.p.h.p.s.

From an inspection of Fig. 359 it will be apparent that the brakes must be applied when the train is on the falling gradient of 1 in 170.

This gradient is equivalent to an accelerating force of $\left(22.4 \times \frac{100}{170} =\right)$ 13.2 lb. per ton of train weight.* Hence the actual retardation during

braking will equal $\left(2 - \frac{13.2}{1.1 \times 102} =\right)$ 1.98 ml.p.h.p.s.

[NOTE.—1.1 is the ratio of the effective weight of the train (214.6 tons) to the dead weight (195 tons).]

The falling gradient of 1 in 133, on which the train is started, is equivalent to an accelerating force of $\left(22.4 \times \frac{100}{133} =\right)$ 16.8 lb. per ton of train weight, or $(16.8 \times \frac{1}{8} \times 195 = 16.8 \times 24.35 =)$ 410 lb. per motor.

Hence during the initial acceleration (up to a speed of 16.8 ml.p.h.) the mean accelerating tractive-effort per motor—on the assumption of 8 lb. per ton for the average train resistance—is $(3500 - 8 \times 24.35 + 410 =)$ 3715 lb.

* Obtained from equation (8), p. 20.

Therefore the mean acceleration—

$$= \frac{3715}{102 \times 26.8} = \frac{3715}{2735} = 1.36 \text{ ml.p.h.p.s.}$$

Duration of the period of initial acceleration—

$$= \frac{16.8}{1.36} = 12.35 \text{ seconds.}$$

Distance run during this period—

$$= \frac{1}{2} \times 16.8 \times 12.35 \times 1.467 = 152.2 \text{ ft.}$$

We now continue the calculation in the same manner (but allow for the effect of the gradient) as in the above example, until a distance of

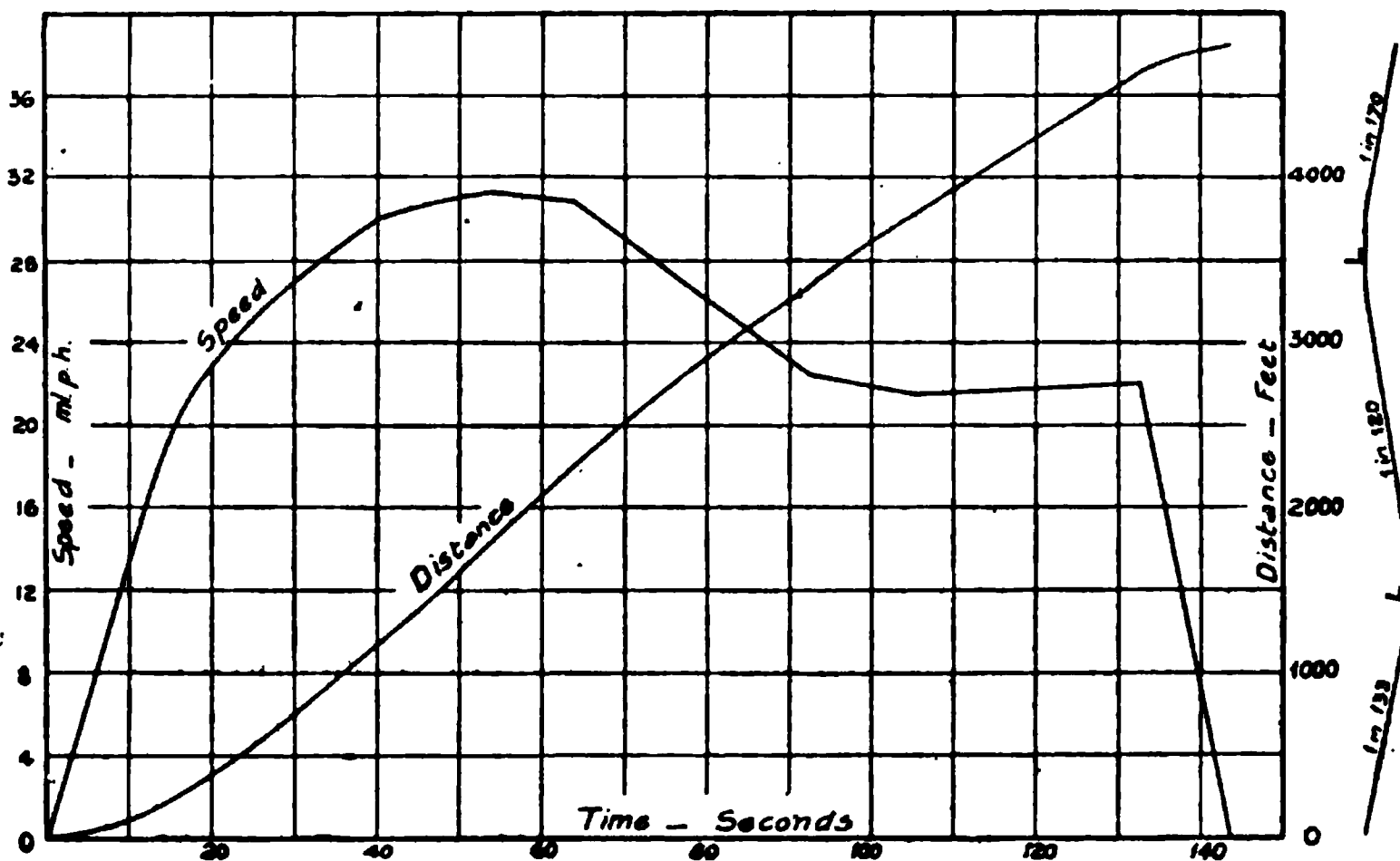


FIG. 360.—Speed-time Curve for Motor-coach Train operating on Track with Curves and Gradients (4800 ft. run at 20 ml.p.h. schedule speed).

1200 ft. has been run. The results of the calculations are given below, and it is only necessary to remark that the last increment of speed (for this period) must be obtained by trial.

We have next 600 ft. of level, but curved, track. For the first 420 ft.

there is a curve of 62 chains radius or $\left(=2 \sin^{-1}\left(\frac{50}{62 \times 66}\right)=\right) 1.4$ degrees,

and for the remainder of the distance there is a curve of 50 chains radius

or $\left(=2 \sin^{-1}\frac{50}{50 \times 66}=\right) 1.73$ degrees. These curves increase the train

resistance by 1.0 and 1.2 lb. per ton respectively, or an increase in resistance of 24 and 29 lb. respectively per motor.

The accelerating tractive-effort is therefore obtained by deducting these values from the appropriate values given in Fig. 357.

A few trials will probably be necessary before the correct distances are obtained.

Next we have to negotiate the rising gradient of 1 in 120. This gradient is equivalent to a retarding force of $\left(22.4 \times \frac{100}{120} = \right) 18.7$ lb. per ton, or $(18.7 \times 24.35 =) 455$ lb. per motor. Hence the mean accelerating (or retarding) tractive-effort is obtained by deducting this force—due to the gradient—from the appropriate values given in Fig. 357. Thus consider the speed-decrement 31.43 to 29.5 ml.p.h. The mean accelerating force on level track, obtained from Fig. 357, is $\left\{ \frac{1}{2}(250 + 360) = \right\} 305$ lb. Hence the net retarding force $= 455 - 305 = 150$ lb. The retardation is therefore $\left(\frac{150}{2735} = \right) 0.055$ ml.p.h.p.s.; whence the time and distance follow in the usual manner.

Before making further calculations it will be advisable to plot the speed-time and distance-time curves for the purpose of making trials to determine the point of cut-off.

The results of the calculations for the speed-time and distance-time curves up to 89 seconds (*i.e.* until the second stretch of level track is reached) are given in Table XV.

TABLE XV
CALCULATION OF SPEED-TIME CURVE FOR RUN ON TRACK WITH GRADIENTS AND CURVES.

Speed.	Net Tractive-effort on level and straight Track.	Tractive-effort due to Gradient or Curve.	Mean Accelerating Tractive-effort.	Speed Increment.	Mean Acceleration.	Time Increment.	Time from Start.	Mean Speed.	Distance Increment.	Total Distance.
ml.p.h.,	lb.	lb.	lb.	ml.p.h.	ml.p.h.p.s.	sec.	sec.	ml.p.h.	ft.	ft.
0	3305	+410	3715	16.8	1.36	12.35	0	8.4	152	0
16.8	3305	+410	3107	2.2	1.135	1.94	12.35	17.9	51	152
19	2090	+410	2140	2.0	.782	2.66	14.3	20	75	203
21	1370	+410	1620	1.5	.592	2.53	16.85	21.75	81	278
22.5	1050	+410	1290	2.5	.472	5.3	19.4	23.75	185	359
25	710	+410	1010	2.5	.37	6.8	24.7	26.25	261	544
27.5	490	+410	810	2.7	.296	9.12	31.5	28.85	386	805
30.2	310	+410	262	0.9	.096	9.4	40.6	30.65	423	1191
31.1	262	-24	227	0.33	.083	4.0	50.0	31.27	184	1614
31.43	250	-29	227	0.33	.083	4.0	54.0	30.46	1562	1798
29.5	360	-455	-150	-1.93	-.055	35.0	89.0			3360

Therefore the distance run during braking is $(\frac{1}{2} \times 21.97 \times 11.1 \times 1.467 =)$ 179 ft., and the coasting distance is $\{\frac{1}{2}(21.47 + 21.97) \times 26.6 \times 1.467 =\}$ 848 ft. Summing up the various distances we obtain a total of 4817 ft.

The complete speed-time and distance-time curves are given in Fig. 360, while the results of the calculations for the coasting and braking periods are given in Table XVI.

TABLE XVI

CALCULATION OF COASTING AND BRAKING PORTION OF SPEED-TIME CURVE FOR RUN ON TRACK WITH GRADIENTS AND CURVES.

Speed.	Mean Train Resistance.	Retarding Force due to Gradient or Curve.	Mean Retarding Force.	Mean Retardation.	Time Increment.	Speed Decrement.	Distance Increment.	Mean Speed.	Time from Start.	Total Distance from Start.
ml.p.h.	lb. per ton.	lb. per ton.	lb. per ton.	ml.p.h.p.s.	sec.	ml.p.h.	ft.	ml.p.h.	sec.	ft.
30.8	12.4	18.7	31.1	.277	28.4	7.85	1093	26.87	64	2259
22.94	11.1	1.2	12.4	.11	13.4	1.47	440	22.2	92.4	3350
21.47	11.1	-13.2	-2.1	-.0187	26.6	-.05	848	21.72	105.8	3790
21.97	..	..	..	1.98	11.1	21.97	179	10.98	132.4	4638
0	..	..	..	..	..	..	..	..	143.5	4817

In cases where speed-time curves are required for runs extending over many gradients the calculations can be carried out more expeditiously by adopting the **analytical method developed by Mr. F. W. Carter**, and described in detail in a paper entitled "Predetermination in Railway Work." * In this method the treatment of problems connected with train movement is based upon the assumption that, within the working range of ordinary continuous-current series traction motors, the relations between the tractive-effort and the current may be represented by a straight line, while the relation between the speed and the current may be represented by a hyperbola. From these premises a series of equations connecting the speed, distance, tractive-effort, and time are developed, and a set of universal speed-time and speed-distance curves are obtained from which those appropriate to the problem can be selected.

* See *Transactions of the American Institute of Electrical Engineers*, vol. 22, p. 133. This paper should be studied by all students interested in the subjects of speed-time curves and energy consumption. Further papers on speed-time curves will be found in vol. 19, pp. 129, 901; vol. 33, p. 1673.

PART II.—ENERGY CONSUMPTION (CONTINUOUS-CURRENT EQUIPMENTS)

One of the characteristic features of electrical engineering is that the energy input to a motor, or a group of motors, performing a definite cycle of operations can be predetermined with a high degree of accuracy when the characteristic curves of the machines are available and the mechanical resistances are known. This feature also applies to electric railway engineering. For instance, the performance of a given electric train, operating to a given schedule in suburban service, can be predetermined with precision, since the uncertain factors (such as train resistance) connected with the problem influence the final results to only a small degree. Hence in making guarantees for the energy consumption of suburban electric trains it is only necessary to add a small allowance (to cover unforeseen contingencies) to the calculated figures; in fact, this allowance is, in many cases, only of the order of 5 per cent. It is now our purpose to show the manner in which these calculations are made.

In order to calculate the energy required by an electric train when operating to a given schedule, it is necessary to have available the speed-time curve corresponding to the conditions of service and the characteristic curves of the driving motors, while a knowledge of the method of control will also be necessary.

In principle, the **method of calculation** is similar to that adopted for the calculation of the speed-time curve, *i.e.* the speed is considered as the independent variable and the increments in the time and current, corresponding to increments in the speed, are obtained. The increments in the energy are then calculated, and the total energy supplied follows by a process of summation.*

The method of procedure is best illustrated by working through an example, and for this purpose we shall consider the 2560-ft. run for which the speed-time curve was calculated in the earlier part of this chapter.

In the calculations which follow, the energy supplied to one motor is calculated, and the total energy supplied to the train is obtained by multiplying by the number of motors. This method possesses an advantage over the direct method of calculating the total energy, since the standard characteristic curves of the motor can be used without modification.

The characteristic curves of the motors under consideration are given in Fig. 32 (p. 49). Of these curves we only require the speed-current curve for the energy calculations, but we shall utilise the efficiency curve later in order to obtain the average efficiency during the period of speed-curve running.

Consider first the **period of rheostatic acceleration** (*i.e.* from the start until a speed of 16.8 ml.p.h. is reached). During this period the current per motor will be assumed to be maintained constant at 225 amperes.†

* The total energy supplied may also be obtained by plotting a power-time curve and integrating this by means of a planimeter.

† In practice, with a limited number of controller notches, the current will fluctuate between maximum and minimum values as the sections of the rheostats are cut out. With suitably-graded rheostats and the controller manipulated to give uniform current-peaks (*e.g.* as is obtained with automatic control), the deviation of the actual conditions from the ideal will not introduce any appreciable errors into the calculation of either the speed or the energy consumption.

With series-parallel control, the input (from the conductor rails) to a pair of motors during the first half of this period (when the motors are in series) will be $225 \times 600 = 135$ kw., and during the second half of the period (when the motors are in parallel) the input will be $2 \times 225 \times 600 = 270$ kw. Hence the energy input per motor for the whole of the initial accelerating period will be * $\left\{ \frac{1}{2}(135 \times \frac{1}{2} \times 13.9 + 270 \times \frac{1}{2} \times 13.9) \right\} = 1409$

kw.-seconds, or $\left(1409 \times \frac{1000}{3600} = \right) 391$ watt-hours.

The energy input for the **period of speed-curve running** is obtained by selecting a series of increments of the speed, calculating the average energy input for each increment, and summing the results.

Thus the interval from 16.8 ml.p.h. to 19 ml.p.h. occupies 2.23 seconds, and the average current (from Fig. 32) is $\left\{ \frac{1}{2}(225 + 160) \right\} = 192$

amperes, so that the average energy input $= \frac{192 \times 600 \times 2.23}{3600} = 71.4$ watt-hours.

Similarly, for the intervals until cut-off, we obtain the following results :—

Speed Increment (ml.p.h.).	Time Interval (seconds).	Average Current (amperes).	Average Energy Input. (watt-hours).
19 to 21	3.16	141	74.2
21 to 22.5	3.29	114	64.4
22.5 to 25	7.76	93	120
25 to 26.1	4.6	83.5	64

The average energy input per motor for the whole run is, therefore, $(391 + 71.4 + 74.2 + 64.4 + 120 + 64 =) 785$ watt-hours. Hence the total

energy consumption for the train is $\left(\frac{785 \times 8}{1000} = \right) 6.28$ kw.-hours, or

$\left(\frac{6.28 \times 5280}{2560} = \right) 12.95$ kw.-hours per train mile.

The specific energy consumption $= \frac{12.95 \times 1000}{195} = 66.4$ watt-hours per ton mile.

* The series and parallel portions of the initial accelerating period are here considered to be of equal duration. A reference to Fig. 110 (p. 142) will show that, due to the internal resistance of the motors, the time of running on the series notches is slightly shorter than that for the parallel notches when the accelerating current per motor is maintained constant. In the present case, assuming a 5 per cent. voltage drop in each motor, the respective times on the series and parallel notches are 6.58 and 7.32 seconds, so that the energy input per motor during the initial accelerating period is 1432 kw. seconds instead of 1409. The specific energy consumption, however, only differs 0.5 per cent. in the two cases.

It is instructive to analyse this energy consumption into its several components. Thus :

$$\text{Energy expended during braking}^* = \frac{0.0283 \times (21.6)^2 \times 214.6 \times 5280}{2560 \times 195}$$

$$= 29.9 \text{ watt-hours per ton mile.}$$

Energy expended against train resistance (while power is on) † .

$$= 4.7 \text{ watt-hours per ton mile.}$$

Energy expended against apparent train resistance during coasting (difference between kinetic energy at 26.1 ml.p.h. and 21.6 ml.p.h.) .

$$= 13.8 \text{ watt-hours per ton mile.}$$

Losses in starting rheostats ‡ .

$$= 10.5 \text{ watt-hours per ton mile.}$$

Losses in motors and gearing (by difference) .

$$= 7.5 \text{ watt-hours per ton mile.}$$

The energy utilised during the run $= 4.7 + 13.8 = 18.5$ watt-hours per ton mile, or 28 per cent. of the energy supplied from the conductor rails. The remaining 72 per cent. is accounted for as follows : 45 per cent. is dissipated in the brake shoes, 12 per cent. is dissipated in the starting rheostats, and 12 per cent. is dissipated in the motors and gearing.

If the kinetic energy possessed by the train at the point of cut-off be considered, we find that 31.6 per cent. of this energy is utilised during coasting, and the remaining 68.4 per cent. is dissipated in the brake shoes.

It will be observed that, although the schedule speed is fairly high

* Obtained from equation (10). See p. 22.

† The energy expended against train resistance over a distance D' is approximately $2 D'/D$ watt-hours per ton mile for each lb. per ton of train resistance, D being the total distance of the run. In the present case the average resistance between 16.8 ml.p.h. and 26.1 ml.p.h. is 6.6 lb. per ton. Hence, since the distance run during starting is 170 ft., and the total distance up to the point of cut-off is 875 ft., we have :—energy expended against train resistance (while power is on)

$$= 2 \times 8 \times \frac{170}{2560} + 2 \times 6.6 \times \frac{(875 - 170)}{2560}$$

$$= 4.7 \text{ watt-hours per ton mile.}$$

‡ This value is obtained as follows : Assuming a 5 per cent. voltage drop in each motor and a constant supply voltage of 600 volts, the times on the series and parallel notches are, respectively, 6.58 and 7.32 seconds. The mean voltage drop in the rheostats during series notching is $[\frac{1}{2} \{ 600(1 - 2 \times 0.05) \}] = 270$ volts, while the value corresponding to the parallel notches is 150 volts. Hence the energy dissipated in the rheostats (per pair of motors) is

$$\left(\frac{225 \times 270 \times 6.58 + 2 \times 225 \times 150 \times 7.32}{3600} \right) =$$

$$248 \text{ watt-hours, which corresponds to } \frac{248 \times 4 \times 5280}{195 \times 2560} = 10.5 \text{ watt-hours per ton mile.}$$

If the internal resistance of the motors is neglected, the loss in the rheostats will be given by $\frac{1}{2}$ (kinetic energy of train at end of initial accelerating period + work done against train resistance). Applying this rule to the above example, we have :

$$\text{Kinetic energy of train at 16.8 ml.p.h.} = \frac{0.0283 \times (16.8)^2 \times 214.6 \times 5280}{2560 \times 195} = 18.1 \text{ watt-hours per ton mile.}$$

$$\text{Work done against train resistance} = 2 \times 8 \times \frac{170}{2560} = 3.36 \text{ watt-hours per ton mile.}$$

Therefore the approximate loss in rheostats $= \frac{1}{2}(18.1 + 3.36) = 10.73$ watt-hours per ton mile.

for such a short run, the energy consumption is not excessive. This result is due to the adoption of a moderately high acceleration and retardation, by which means a fairly long coasting period is obtained, *e.g.* the duration of coasting period being 48.5 per cent. of the running period.

The effect of the acceleration and the rate of braking on the energy consumption has been considered from a general point of view in Chapter III. We will investigate the effect of, say, a 17.5 per cent. reduction in the initial acceleration for the above service, the schedule speed, rate of braking, and other conditions being the same.

The mean tractive-effort per motor to give an acceleration of 1.0 ml.p.h.s. (allowing 8 lb. per ton for train resistance) is $(1.0 \times 102 \times 26.8 + 8 \times \frac{1}{8} \times 195 =)$ 2928 lb., which corresponds to a current of 195 amperes. The speed of the train, corresponding to this current and normal voltage, is 17.6 ml.p.h. Hence the duration of the initial

accelerating period $= \frac{17.6}{1.0} = 17.6$ seconds.

The average energy input (per motor) during the initial accelerating period $= \frac{1}{2} \left(195 \times 600 \times \frac{17.6}{2} + 2 \times 195 \times 600 \times \frac{17.6}{2} \right) \times \frac{1}{3600} = 429$ watt-

hours. By calculating the speed-time curve in the manner indicated above, we find that power must be cut off at 41 seconds when the speed is 26.8 ml.p.h., while the brakes must be applied at 77.5 seconds when the speed is 23 ml.p.h. The energy input (per motor) for the whole run is 840 watt-hours, or 7 per cent. greater than that for the higher acceleration. The duration of the coasting period in the present instance is 41 per cent. of the running period.

The energy account for this run is as follows :

Energy dissipated in the brake shoes .	= 33.9 watt-hours per ton mile.
Energy expended against train resistance (while power is on) .	= 6.8 watt-hours per ton mile.
Energy expended against (apparent) train resistance during coasting .	= 12.1 watt-hours per ton mile.
Losses in starting rheostats .	= 11.5 watt-hours per ton mile.
Losses in motors and gearing .	= 6.8 watt-hours per ton mile.

The lower acceleration, however, will result in a **lower maximum output per motor** and a lower maximum load on the sub-station. Thus, in

the first case, the maximum output per motor $= 3500 \times \frac{16.8}{60} \times \frac{5280}{33000} = 156$

H.P.; while, in the second case, this becomes $2928 \times \frac{17.6}{60} \times \frac{5280}{33000} = 137.5$

H.P. Similarly the **maximum input** to the train, in the first case, is

$\left(\frac{225 \times 600 \times 8}{1000} = \right)$ 1080 kw., while, in the second case, the maximum input

is $\left(\frac{195 \times 600 \times 8}{1000} = \right)$ 936 kw., which is 13.4 per cent. lower than the former.

It will be interesting to ascertain the difference in the **heating of the motors** in the two cases. Although the heating is due to core, friction, and I^2R losses, we shall only consider the I^2R losses, since the other losses will not differ materially in the two cases. Hence the heating may be considered as proportional to the root-mean-square (R.M.S.) current for the cycle (*i.e.* from start to start).

The current-time curves (for one motor) are given in Figs. 361, 362, together with the kw.-time curves. By converting the current-time curve into a (current)²-time curve, and integrating the latter over the period from start to start, we can obtain the R.M.S. value of the current for the cycle. Thus, for the first run, the mean square of the current, over the period from start to start, $= \frac{991850}{109} = 9100$. Therefore the R.M.S. current = 95.4 amperes.

For the second run, the mean square of the current, over the period from start to start, $= \frac{944600}{109} = 8670$. Therefore the R.M.S. current = 93.1 amperes.

The heating of the motors will, therefore, be only slightly reduced by adopting the lower acceleration, and practically the same size of motor will be required in each case.

The comparisons between the two runs may be summarised thus :

Initial acceleration (ml.p.h.p.s.)	1.21	1.0
Rate of braking (ml.p.h.p.s.).	2.0	2.0
Initial accelerating current per motor (amp.)	225	195
R.M.S. current per motor (amp.)	95.4	93.1
Specific energy consumption (wh./t.ml.)	66.4	71.1
Total energy consumption (kw.h.)	12.95	13.9
Maximum input from conductor rails (kw.)	1080	936
Average input from conductor rails (kw.)	202	222
Maximum output from motors (H.P.)	1250	1100
Maximum speed (ml.p.h.)	26.1	26.8
Speed at commencement of braking (ml.p.h.)	21.6	23
Time from start to point of cut-off (sec.)	35	41
Duration of coasting period (sec.)	43.2	36.5
Duration of braking period (sec.)	10.8	11.5
Energy utilised (wh./t.ml.)	18.5	18.9
Energy dissipated in brakes (wh./t.ml.)	29.9	33.9
Energy dissipated in starting rheostats (wh./t.ml.)	10.5	11.5
Energy dissipated in motors and gears (wh./t.ml.)	7.5	6.8

It is apparent that, from the energy point of view, the adoption of the higher acceleration has considerable advantages. The only disadvantages are : (1) a higher peak load on the sub-stations, (2) a slightly increased maintenance on the rolling stock and equipment. Of course, if the acceleration were increased to, say, 1.5 ml.p.h.p.s., larger equipments would be necessary, and in this case it is quite possible that, although the specific energy consumption would be reduced, the total energy consumption may be increased. Moreover, this high acceleration would increase considerably the peak load on the sub-stations, thereby necessitating more expensive plant and larger feeders.

The influence of the rate of braking on the energy consumption is shown by the following figures, which have been calculated for the above train. The initial acceleration has been chosen at 1.21 ml.p.h.p.s., so that the results can readily be compared with those obtained previously, and which are given below for comparison.

Average rate of braking (ml.p.h.p.s.).	2.0	2.75	1.5
Initial acceleration (ml.p.h.p.s.)	1.21	1.21	1.21
Time at which power is cut off (sec.).	35	33	43
Time at which brakes are applied (sec.)	78.2	81.6	69.5
Maximum speed (ml.p.h.)	26.1	25.6	27.6
Speed at commencement of braking (ml.p.h.)	21.6	20.3	24.5
Duration of coasting period (sec.)	43.2	48.6	26.5
Duration of braking period (sec.)	10.8	7.4	19.5
Specific energy consumption (wh./t.ml.)	66.4	64	75.3
Energy dissipated in brakes (wh./t.ml.)	29.9	26.4	38.5

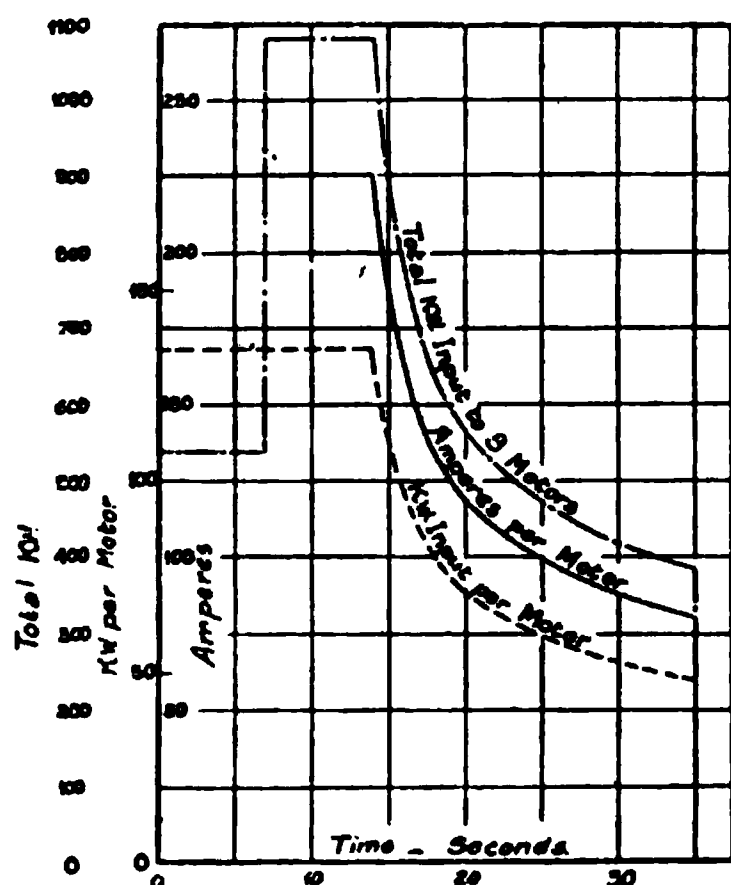


FIG. 361.

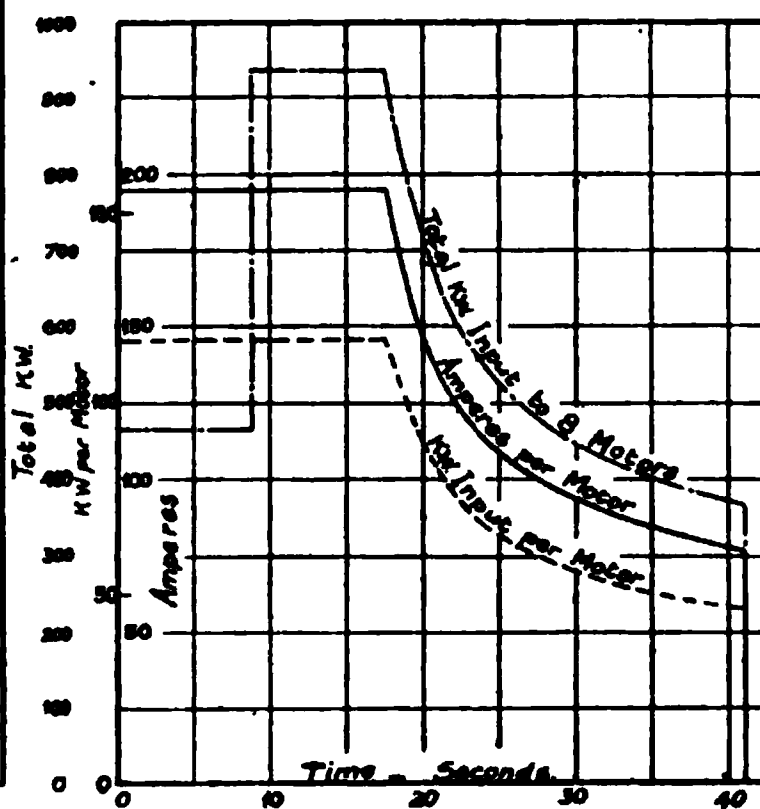


FIG. 362.

Current and Power Curves for 175-ton Motor-coach Train.

Thus, considering the normal rate of braking to be 2.0 ml.p.h.p.s., a reduction of 25 per cent. in the rate of braking increases the energy consumption by 13 per cent.; while, if the rate of braking be increased 37.5 per cent., the energy consumption will only be reduced by 4 per cent.

The relation between the rate of braking and the energy consumption is shown better by the curve in Fig. 363, which is plotted from the above results. It is apparent, therefore, that, for the above service very little advantage is gained by the adoption of a braking rate above 2.0 ml.p.h.p.s.

The influence of the length of the run on the energy consumption (when the schedule speed is constant) is illustrated in Fig. 364,* which is plotted from test results for a number of runs with 175-ton motor-coach trains. As the runs were all made with the same driver, the effect

* From a paper by Mr. Roger T. Smith on "Some Railway Conditions Governing Electrification" (*Journal of the Institution of Electrical Engineers*, vol. 52, p. 293).

of the personal element on the performance will be practically the same for each run.

Effect of Gear Ratio and Method of Control on Energy Consumption.—Since the energy consumption of a train operating to a given schedule is influenced by the duration of the coasting period, it is clear that any conditions of operation which will increase the coasting period will result in reduced energy consumption.* When the length of the run, the schedule speed, and the rate of braking are fixed, the coasting period will be affected only by (1) the initial acceleration and (2) the free-running speed. With short runs the initial acceleration will have the greater influence on the energy consumption, but with longer runs the energy consumption will be largely dependent on the free-running speed.

Now, if with a given equipment the gear-ratio be changed, the initial acceleration and the free-running speed will be changed; consequently

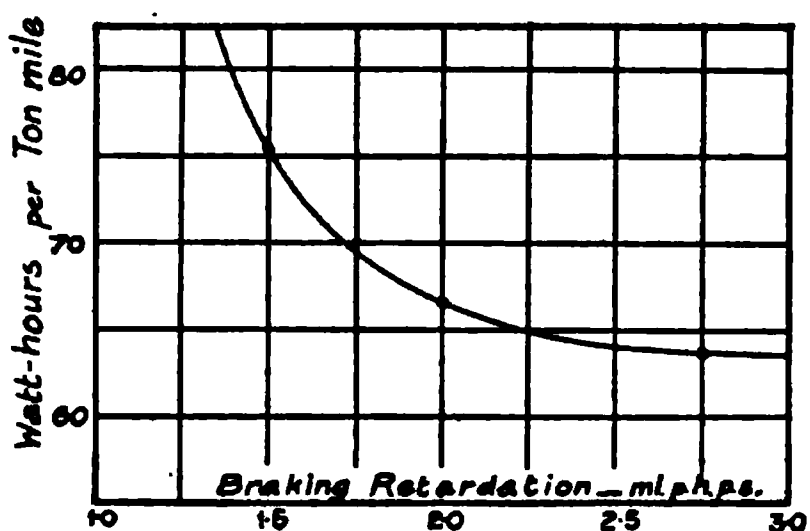


FIG. 363.—Effect of Rate of Braking on Specific Energy Consumption (2560 ft. run at 16 ml.p.h. schedule speed; acceleration = 1.21 ml.p.h.p.s.).

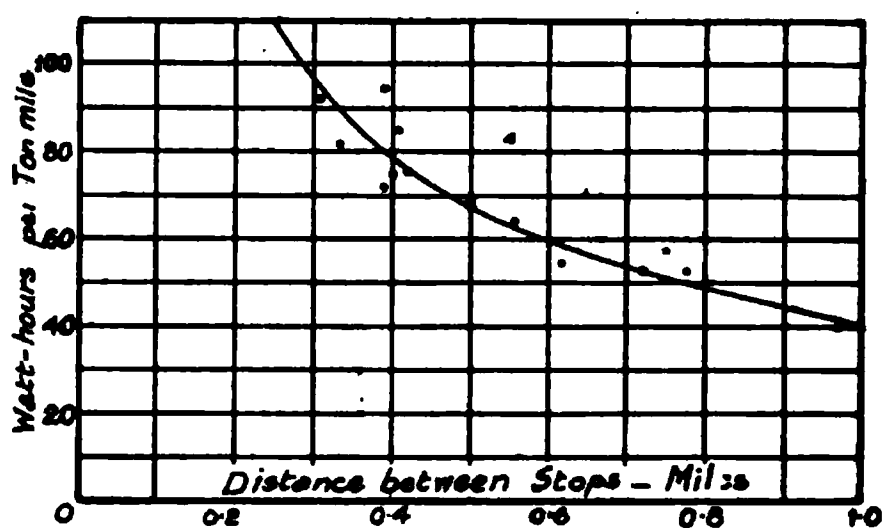


FIG. 364.—Influence of Length of Run on Specific Energy Consumption (weight of train 175 tons; schedule speed 17 ml.p.h.).

the saving resulting from, say, a higher initial acceleration will be offset by the longer duration of the speed-curve-running period, due to the lower free-running speed (assuming the schedule speed to be unaffected by the change). Whether or not the energy consumption will be affected by the change of gearing will depend on the relative values of the energy consumption for the accelerating and speed-curve-running periods in each case, and a definite decision can only be arrived at by working through the speed-time curves and calculating the energy consumption in the usual manner.

In order to illustrate this point we show, in Fig. 367, speed-time curves—for the above 175-ton motor-coach train—corresponding to gear ratios of 2.5:1, 3.5:1, and 4.5:1, the schedule speed, distance of run, rate of braking, and accelerating current being the same in each case. The energy consumption has also been calculated, and the values are given in Table XVII (p. 446).

Before giving these results it will be desirable to indicate the modifications required to the above data to allow for the change of gear ratio.

* This statement assumes that the increased coasting is obtained by altering either the initial acceleration, or the braking, or both; the acceleration on the speed-curve being unaltered. In other words, the gear ratio is assumed to remain constant.

The characteristic curves of Fig. 32 (p. 49) are modified in the following manner. Considering the speed curve, if V denotes the (train) speed corresponding to a current I and gear ratio γ , then the speed V_1 corresponding to a gear ratio γ_1 and the same current is given by $V_1 = V\gamma/\gamma_1$.

The tractive-effort curve is modified in a similar manner, except that the ratio γ/γ_1 is inverted. Thus, if F, F_1 denote the tractive-efforts corresponding to a given current, then $F_1 = F\gamma_1/\gamma$.*

The modified values of the speed and tractive-effort are as follows:—

Current (amperes)	225	175	125	100	75	50
Speed, 2.5 : 1 gear; 36-in. wheels (ml.p.h.)	23.5	25.6	29.3	32.5	38.1	51.4
Speed, 4.5 : 1 gear; 36-in. wheels (ml.p.h.)	13.07	14.25	16.25	18	21.2	28.6
Tractive-effort, 2.5 : 1 gear; 36-in. wheels (lb.)	2500	1800	1130	805	500	214
Tractive-effort, 4.5 : 1 gear; 36-in. wheels (lb.)	4500	3240	2030	1405	900	385

The change in the gear ratio will affect the apparent train resistance during coasting. The values on p. 428 and Fig. 351 must therefore be modified to correspond to the change in the gearing, the modification being effected by the method given in the footnote on p. 428. The results of these modifications are as follows:—

Speed of train (ml.p.h.)	10	15	20	25	30	35	40
Apparent train resistance for gear ratio 2.5 : 1 (lb. per ton)	7.6	8.16	9.13	10.25	11.45	12.7	14.1
Apparent train resistance for gear ratio 4.5 : 1 (lb. per ton)	10	11.1	12.4	13.7	15.1	..	..

The effective weight of the train will also be affected by the change in the gear ratio due to the change in the ratio of the speed of the train to the speed of the armatures. By the application of equation (7), p. 19, we obtain the effective weight, corresponding to a gear ratio of 2.5 : 1, as 210.6 tons, while the effective weight corresponding to a gear ratio of 4.5 : 1 is 217 tons.

Hence, for an accelerating current of 225 amperes per motor, the initial acceleration, with a gear ratio of 2.5 : 1, is

$$\left(\frac{2500 - \frac{1}{8} \times 195 \times 8}{\frac{1}{8} \times 210.6 \times 102} = \frac{2305}{2685} \right) 0.86 \text{ ml.p.h.p.s. ;}$$

while, with a gear ratio of 4.5 : 1, the initial acceleration, with the same current per motor, is

$$\left(\frac{4500 - \frac{1}{8} \times 195 \times 8}{\frac{1}{8} \times 217 \times 102} = \frac{4305}{2770} \right) 1.55 \text{ ml.p.h.p.s.}$$

* This assumes that the gear and axle-friction losses are the same in each case, which assumption may be considered to be approximately correct, since although the speeds of the axle and gearing (corresponding to a given speed of the armature) are increased with a reduction in the gear ratio, the tooth and bearing pressures are reduced.

TABLE XVII

SUMMARY OF THE RESULTS OF CALCULATIONS FOR A 175-TON MOTOR-COACH TRAIN OPERATING AT A SCHEDULE SPEED OF 16 ML.P.H. ON A RUN OF 2560 FT. ON LEVEL TRACK, WITH STOPS OF 20 SECONDS DURATION.

Gear ratio	2.5	3.5	4.5
Initial accelerating current per motor (amp.)	225	225	225
Rate of braking (ml.p.h.p.s.)	2.0	2.0	2.0
Initial acceleration (ml.p.h.p.s.)	0.86	1.21	1.55
Specific energy consumption (wh./t.ml.)	84	66.4	64
Maximum input from conductor rails (kw.)	1080	1080	1080
Average input from conductor rails (kw.)	262	202	200
Maximum output from motors (H.P.)	156	156	156
Free-running speed of train (ml.p.h.)	43.5	38.5	32.5
Maximum speed of train during run (ml.p.h.)	28	26.1	25.5
Speed of train when rheostats are cut out (ml.p.h.)	23.5	16.8	13.1
Speed of train at commencement of braking (ml.p.h.)	24	21.6	21.8
Mean retardation during coasting (ml.p.h.p.s.)	0.096	0.103	0.117
Time from start to point of cut off (sec.)	35	35	46.5
Duration of coasting period (sec.)	42	43.2	31.6
Duration of braking period (sec.)	12	10.8	10.9
Energy utilised (wh./t.ml.)	18	18.5	17.5
Energy dissipated in brakes (wh./t.ml.)	36.9	29.9	30.5
Energy dissipated in starting rheostats (wh./t.ml.)	20.6	10.5	6.4
Energy dissipated in motors and gears (wh./t.ml.)	8.5	7.5	9.6
R.M.S. current per motor (amp.)	121.5	95.4	80.8
Peripheral speed of gearing at free-running speed (ft./min.)	2260	2260	2000
Diameter of pitch circle of gear wheel (in.)	22.5	24.5	25.8

The relation between the energy consumption and the gear ratio for the above conditions of operation is shown in Fig. 365. It will be observed that for gear ratios below 3.0 the energy consumption increases rapidly as the gear ratio is reduced, while for gear ratios between 3.75 and 4.5 the energy consumption is not materially affected by a change in the gear ratio. But if the gear ratio is increased above 4.5:1, the energy consumption will increase rapidly, reaching 78.6 watt-hours per ton mile for a gear ratio of 5.3:1, which is the highest gear ratio with which the service can be run. In this case power must be kept on for 76 seconds, and the brakes must be applied immediately after power is cut off.

In considering the effect of the gear ratio on the energy consumption we have neglected the mechanical limitations, such as (1) the clearance between the lowest point of the gear case and the track, and (2) the peripheral speed of the gearing. These limitations are discussed in detail in Chapter XVII (see p. 363). It is apparent, therefore, that

in the selection of a suitable gear ratio for a given equipment, the mechanical limitations must be carefully considered as well as the energy consumption.

The comparison between the above runs is greatly facilitated by plotting the values of the energy expended in the various parts of the equipment against the gear ratio, as shown in Fig. 366. We have in this diagram (and also in Fig. 367) an explanation of the rapid rise of the energy consumption when the gear ratio is increased above 4.5 : 1; for, although the energy dissipated in the rheostats is reduced, the energy dissipated in the motors and gearing, as well as in the brakes, is increased.

The increased losses in the motors are principally friction losses, consequent upon the high armature speed. For instance, in the particular motor for which the characteristic curves are given in Fig. 32,

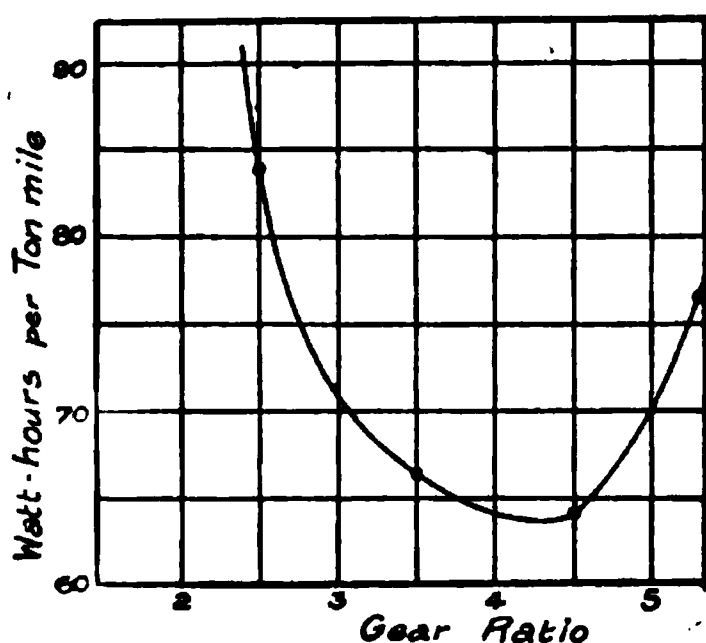


FIG. 365.

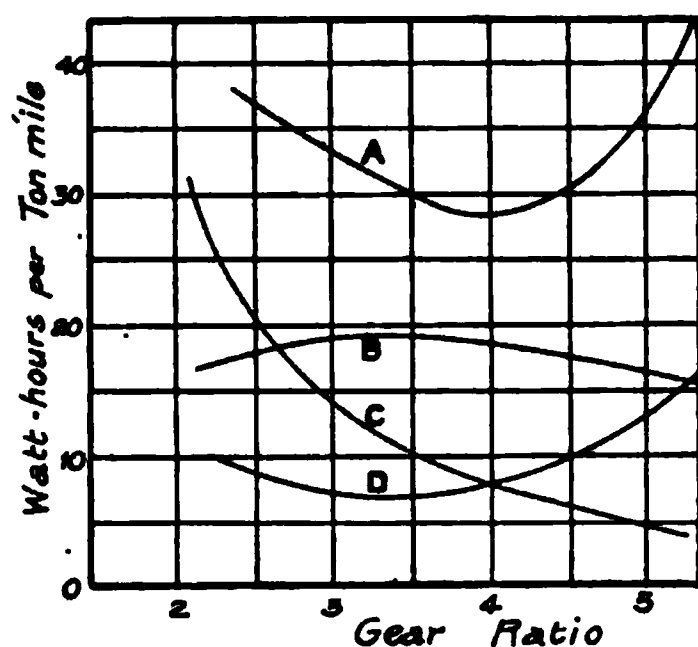


FIG. 366.

Effect of Gear Ratio on Energy Consumption of 175-ton Motor-coach Train (2560 ft. run at 16 ml.p.h. schedule speed).

- A. Energy dissipated in brake shoes.
- B. Energy expended in overcoming train resistance.
- C. Energy dissipated in rheostats.
- D. Energy dissipated in motors and gearing.

the friction (and gear) losses at an armature speed of 1200 r.p.m. (corresponding to a train speed of 26 ml.p.h. with a gear ratio of 5.3 : 1) are approximately 20 per cent. of the input to the motor. With a high gear ratio a large portion of the run must be made at speeds in the neighbourhood of free-running, and as this condition usually corresponds to a high armature speed, the average equipment efficiency during this period is low. This point is clearly shown by the curves of Fig. 367, which refer to the above runs, with an additional curve for the maximum gear ratio (5.3 : 1) added.* Comparing the runs with gear ratios of 3.5 : 1 and 5.3 : 1, we find that the mean efficiencies during the periods of speed-curve running are 86.8 per cent. and 73.4 per cent. respectively.

The curves of Fig. 367 also indicate the **ideal conditions for obtaining a low energy consumption** with the standard method of series-

* The points for the portion of the efficiency curve corresponding to speed-curve running are obtained directly from the motor efficiency curve (Fig. 32, p. 49), while the points for the portion corresponding to the initial acceleration are obtained from the ratio of the output to the input, the output being (kinetic energy of train + work done against train resistance).

parallel control. Thus, suppose it were possible to adopt the 5.3:1 gear for the initial accelerating period, and to change this gear to 3.5:1 at a speed of 17.25 ml.p.h. (corresponding to the intersection of the speed-time curves for these gear ratios). We should then be able to cut off power earlier (e.g. at 30 seconds), to coast longer, and to apply the brakes at a lower speed than if we made the run with the 3.5:1 gear throughout. The specific energy consumption for this method of operation reduces to 57.6 watt-hours per ton mile, of which 27 watt-hours per ton mile are expended in the brakes.

Of course such a method of operation is quite impracticable, but

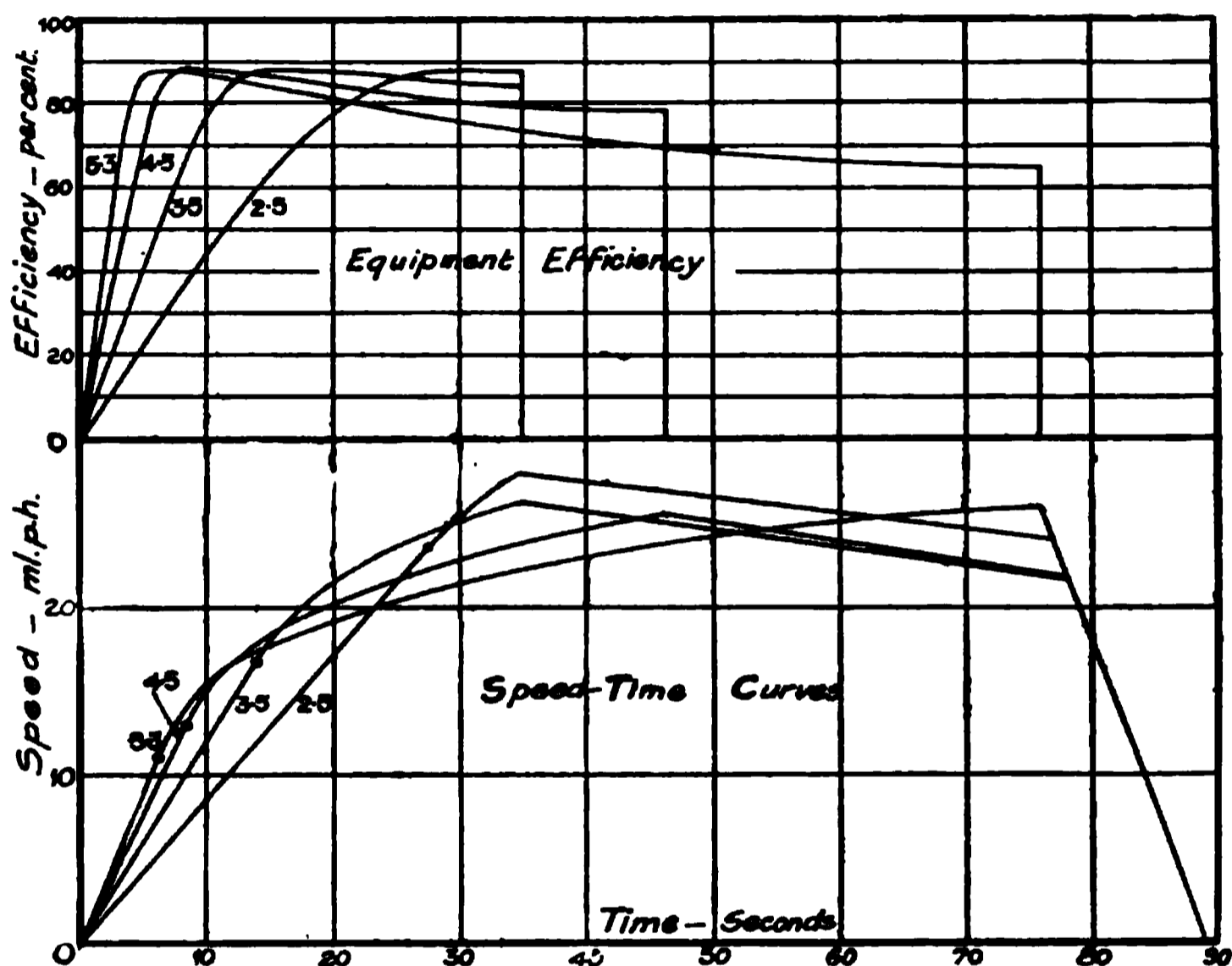


FIG. 367.—Speed-time and Equipment-efficiency Curves for Motor-coach Train (2560 ft. run at 16 ml.p.h. schedule speed). NOTE.—The numbers placed against the curves denote the gear ratio. The points marked ● indicate the commencement of the speed-curve-running periods.

with motors designed for “tap-field” control we can obtain conditions somewhat similar to the above. Thus, at starting, the full field winding would be used, thereby giving a low speed at which the rheostats are cut out, while for the speed-curve-running period the field tapplings would be used, thereby enabling this portion of the run to be made at a moderately high speed, so as to obtain a long coasting period. The effect of this method of control on the energy consumption is considered below.

Energy Consumption of Equipments Operating on various services.—In the above discussion we have considered conditions of service which are typical for city lines. Now, with an extensive system of electrification—involving the electrification of city, suburban, and interurban lines—the traffic department would require the suburban and interurban trains to be scheduled for a faster service than the city

trains. Hence, if the same trains are operated over both city and interurban routes, the gear ratio cannot be selected to give the most economical operation on each system, because, as we have shown above, a moderately high gear ratio is required for city service, and this gear ratio would not give the required schedule speed on the interurban service. For instance, suppose the average run of 5000 ft. is to be made at a schedule speed of 24.5 ml.p.h. with stops of 20 seconds' duration. The running time is therefore 119 seconds. A reference to

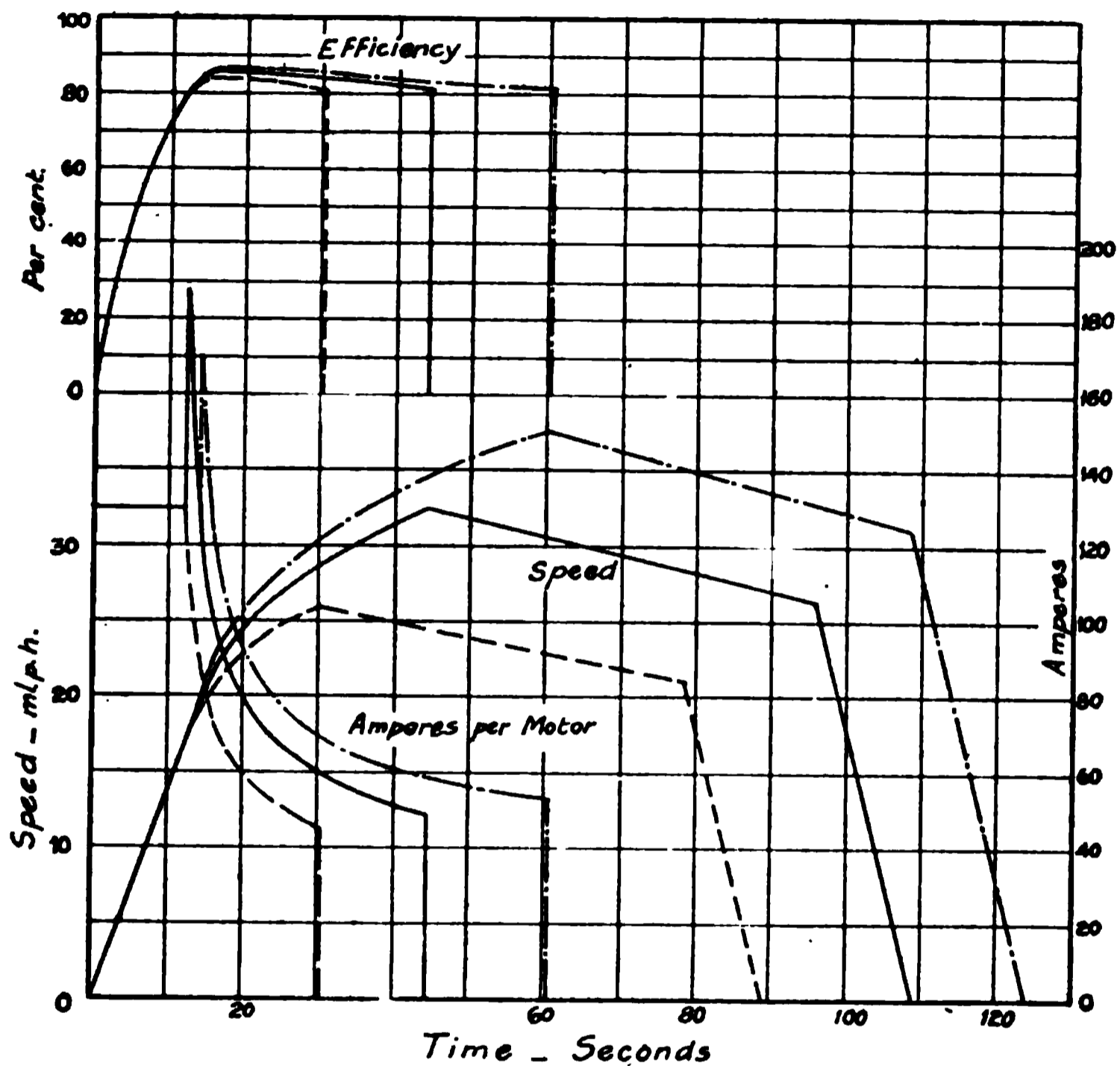


FIG. 368.—Speed, Current, and Efficiency Curves for Motor-coach Train with Field-control Equipments.

--- Full field.
— Normal field.
- . - . - Minimum field.

p. 431 will show that the above equipment, with a gear ratio of 3.5 : 1 and 36-in. wheels, is quite incapable of operating to this schedule. It would therefore be necessary to adopt a lower gear ratio (of about 2.0 : 1 to 2.5 : 1); and, in order to avoid an excessive gear velocity at free-running speed (which in this case would be of the order of 45 to 50 ml.p.h.), the diameter of the driving wheels would probably be increased to 43.5 in. A reference to Fig. 365 will show that such an equipment would have a high energy consumption when operating on the city service.

Moreover, if a compromise in the gear ratio be adopted, the energy consumption for the suburban and interurban services will be higher than that of a train equipped with the correct gear ratio for these services.

These disadvantages are to some extent minimised by the adoption of **equipments with tap-field control**. For example, the motors may be provided with two tappings on each field spool, so that three field strengths could be obtained with a given value of the armature current. The full field winding would be used for the initial acceleration in each of the above services, while the field tappings would be used for obtaining the higher speeds required for the suburban and interurban routes. The gear ratio would be selected to give a moderately high acceleration, so that the train could be operated economically in city service.

Field control, therefore, *considerably extends the flexibility of the equipment*, and, with a suitable selection of the motor, *one class of equipment will be capable of operating on widely different services without the energy consumption, on any of the services, being excessive*. This feature of field-control equipments can be better illustrated by considering a specific example.

Thus, suppose we have a train consisting of two 36-ton motor-coaches with the equipments arranged for field control. Each motor-coach is equipped with four 75-H.P., 500-volt, three-speed series motors, of which the characteristic curves are shown in Fig. 31 (p. 48). The coach-bodies are of the same dimensions as those in the above examples. The wheels are 43.5 in. in diameter, and the gear ratio is 3.9 : 1. The weight of the train loaded with passengers is 78.75 tons, and the effective weight is 86.5 tons.

Let us calculate the energy consumption of this train when operating on level track to various schedules, assuming the retardation during braking to be 2.0 ml.p.h.p.s. in all cases.

The train resistance is given by the equation $r = 4.1 + 0.055V + 0.0042V^2$, and, by making a suitable allowance for the motor and gear friction during coasting, we obtain the following values for the apparent train resistance :—

Speed of train (ml.p.h.)	.	.	10	20	30	40	50
Train resistance (lb./ton)	.	.	5.1	6.9	9.6	13	17.4
Apparent train resistance (lb./ton)			8.5	10.8	14	17.8	22.4

The speed-current and torque-current curves of Fig. 31 are now converted into curves of speed and accelerating tractive-effort, from which we obtain the following values for the free-running speeds of the train : 33.5 ml.p.h. with the full field winding, 42.5 ml.p.h. with normal field winding, 47.5 ml.p.h. with the minimum field winding. [NOTE.—The ratio of the field turns for the full, normal, and minimum field windings are respectively 1.0, 0.667, 0.5.]

First, consider the train to operate on a service with 2.06 stops per mile, at a schedule speed of 16 ml.p.h., the duration of each stop being 20 seconds. The distance between the stops is 2560 ft., and the running time is 89 seconds.

For this run the motors will be operated with the full field winding throughout. By calculating the speed-time curve (see Fig. 368) we find that the initial acceleration (corresponding to a mean accelerating current of 130 amperes per motor) is 1.35 ml.p.h.p.s. and occupies 12.6 seconds, while the power is cut off at 30.1 seconds from the start—when the speed is 26 ml.p.h. The train coasts for 48.4 seconds, and the brakes are applied when the speed is 21 ml.p.h. The specific energy

consumption is 68·7 watt-hours per ton mile, while the total energy consumption is 5·4 kw. hours per train mile. The R.M.S. current per motor for the run is 51·7 amperes. The various steps in the calculation are given in Table XVIII.

TABLE XVIII

CALCULATION OF ENERGY CONSUMPTION FOR TWO-CAR TRAIN. LENGTH OF RUN = 2560 FT. SCHEDULE SPEED = 16 M.P.H. DURATION OF STOP = 20 SEC. BRAKING RETARDATION, 2·0 M.P.H.P.S.

Speed.	Net Tractive-effort	Speed Increment.	Mean Accelerating Tractive-effort.	Mean Acceleration.	Time Increment.	Total Time from Start.	Distance Increment.	Total Distance.	Current per Motor.	Mean Current per Motor.	Mean Energy Input per Motor.
ml.p.h.	lb.	ml.p.h.	lb.	ml.p.h. p.s.	sec.	sec.	ft.	ft.	amp.	amp.	watt-hrs.
0	1490					0		0	130		
		17	1490	1·35	12·6		157			130	170
17	1490					12·6		157	130		
		2·5	1215	1·1	2·3		61			107·5	34·3
19·5	940					14·9		218	85		
		2·5	742	0·67	3·7		113			74·5	38·3
22	545					18·6		331	64		
		3·0	432	0·39	7·7		264			56·5	60
25	320					26·3		595	49		
		1·0	292	0·27	3·8		141			47	24·8
26	265					30·1		736	45		
		-5·0	..	-0·103	48·4		1672				
21	..					78·5		2408	..		
		-10·5	..	-2·0	10·5		162				
0	..					89		2570	..		
Total											327·4

[NOTE.—Full field throughout.]

Energy consumption = $8 \times \frac{327.4}{1000} \times \frac{5280}{2560} = 5.4$ kw. hours per train mile.

Specific energy consumption = $\frac{5.4 \times 1000}{78.75} = 68.7$ watt-hours per ton mile.

Second, consider the train to operate on a service in which the average run of 3900 ft. has to be made at a schedule speed of 20·6 ml.p.h., with stops of 20 seconds' duration. The running time is therefore 109 seconds. For this run the initial acceleration is made with the full field winding, and the acceleration on the speed-curve is made with the normal field winding. When the transition from field to normal field is made, a sudden increase in the current will occur. This increase in the current can readily be obtained from the characteristic curves of the motor (Fig. 31). Thus, assuming the transition to be made at a speed of 17 ml.p.h., we obtain the currents from the speed curves (of Fig. 31) corresponding to this speed, which currents are 130 amperes for full

field and 188 amperes for normal field. From this point the calculation of the speed-time curve and energy consumption is made in the usual manner, the various steps in the process being given in Table XIX.

TABLE XIX

CALCULATION OF ENERGY CONSUMPTION FOR TWO-CAR TRAIN. LENGTH OF RUN = 3900 FT. SCHEDULE SPEED = 20·6 ML.P.H. DURATION OF STOP = 20 SEC. BRAKING RETARDATION = 2·0 ML.P.H.P.S.

Speed.	Net Tractive-effort.	Speed Increment.	Mean Accelerating Tractive-effort.	Mean Acceleration.	Time Increment.	Total Time from Start.	Distance Increment.	Total Distance.	Current per Motor.	Mean Current per Motor.	Mean Energy Input per Motor.
ml.p.h.	lb.	ml.p.h.	lb.	ml.p.h.p.s.	sec.	sec.	ft.	ft.	amp.	amp.	watt-hrs.
0	1490	17	1490	1·35	12·6	0	157	0	130	130	170
17	(1490) (2200)	2·5	1770	1·6	1·56	12·6	42	157	(130) (188)	159	34·5
19·5	1340	2·5	1100	1·0	2·5	14·2	76	199	130	113	39
22	860	3·0	715	0·65	4·6	16·7	160	275	96	85·5	55
25	570	3·0	480	0·43	6·9	21·3	269	435	75	68·5	75
28	390	4·5	305	0·28	16·3	28·2	724	704	62	55·5	126
32·5	220	-6·1	..	-0·12	51·3	44·5	2217	1428	49		
26·4	..	-13·2	..	-2·0	13·2	95·8	255	3645			
0	..					109		3900			
Total											499·5

[NOTE.—Full field, 0–17 ml.p.h. ; normal field, 17–32·5 ml.p.h.]

Energy consumption = $\frac{8 \times 499\cdot5}{1000} \times \frac{5280}{3900} = 5\cdot41$ kw. hours per train mile.

Specific energy consumption = $\frac{5\cdot41 \times 1000}{78\cdot75} = 68\cdot7$ watt-hours per ton mile.

For the run under consideration, power is cut off at 44·5 seconds (when the speed of the train is 32·5 ml.p.h.), and the brakes are applied at 95·8 seconds from the start (when the speed is 26·4 ml.p.h.). The specific energy consumption is 68·7 watt-hours per ton mile, the total energy consumption is 5·41 kw. hours per train mile, and the R.M.S. current is 55·6 amperes.

Third, consider the train to operate on a service in which the average run of 5100 ft. has to be made at a schedule speed of 24·1 ml.p.h., the duration of the stops being 20 seconds, as above. The running time is therefore 124 seconds.

In this case the speed-curve-running period is made with the minimum tap of the field winding in circuit. The initial acceleration is made with the full field winding, the mean current being 130 amperes. The transition to the normal field winding is made at a speed of 17 ml.p.h., while the transition from normal to minimum field is made at a speed of 19.5 ml.p.h.

The various steps in the calculation of the speed-time curve and energy consumption are given in Table XX.

TABLE XX

CALCULATION OF ENERGY CONSUMPTION FOR TWO-CAR TRAIN. LENGTH OF RUN = 5100 FT. SCHEDULE SPEED = 24.1 ML.P.H. DURATION OF STOP = 20 SEC. BRAKING RETARDATION = 2.0 ML.P.H.P.S.

Speed.	Net Tractive-effort.	Speed Increment.	Mean Accelerating Tractive-effort.	Mean Acceleration.	Time Increment.	Total Time from Start.	Distance Increment.	Total Distance.	Current per Motor.	Mean Current per Motor.	Mean Energy Input per Motor.
ml.p.h.	lb.	ml.p.h.	lb.	ml.p. h.p.s.	sec.	sec.	ft.	ft.	amp.	amp.	watt-hrs.
0	1490					0		0	130		
		17	1490	1.35	12.6		157			130	170
17	(1490) (2200)					12.6		157	(130) (188)		
		2.5	1770	1.6	1.56		42			159	54.5
19.5	(1340) (1810)					14.2		199	(130) (170)		
		2.4	1505	1.36	1.77		54			150	37
21.9	1200					15.9		253	130		
		3.1	980	0.89	3.5		121			113	55
25	760					19.4		374	96		
		3.0	640	0.58	5.2		202			87.2	62.6
28	520					24.6		576	79		
		4.0	420	0.38	10.5		462			72	105
32	320					35.1		1038	64		
		4.0	262	0.24	16.8		840			60	140
36	205					51.9		1878	56		
		1.5	187	0.17	8.8		474			54.5	66.6
37.5	170					60.7		2352	53		
		-6.5		-0.136	47.8		2400				
31						108.5		4752			
		-15.5		-2.0	15.5		353				
0						124		5105			
Total											690.7

[NOTE.—Full field, 0–17 ml.p.h.; normal field, 17–19.5 ml.p.h.; minimum field, 19.5–37.5 ml.p.h.]

Energy consumption = $\frac{8 \times 690.7}{1000} \times \frac{5280}{5100} = 5.72$ kw. hours per train mile.

Specific energy consumption = $\frac{5.72 \times 1000}{78.75} = 72.6$ watt-hours per ton mile.

For the run under consideration, power is cut off at 60·7 seconds from the start (when the speed is 37·5 ml.p.h.), while the brakes are applied at 108·5 seconds from the start (when the speed is 31 ml.p.h.). The specific energy consumption is 72·6 watt-hours per ton mile, the total energy consumption is 572 kw. hours per train mile, and the R.M.S. current is 60 amperes.

The speed-time curves for the above runs are shown in Fig. 368, in which figure are also shown the current curves and the equipment-efficiency curves.

The equipment is also capable of operating other fast suburban services, as shown below.

Distance between Stops.		Duration of Stop.	Schedule Speed.	Running Time.	Time of Cut off.	Duration of Coasting Period.	Specific Energy Consumption.	R.M.S. Current per Motor.
ft.	miles.	sec.	ml.p.h.	sec.	sec.	sec.	wh/t.ml.	amp.
5370	1·02	20	25·5	124	79	27	80	62·2
6150	1·17	„	26·4	139	79	43·3	70	59·6
8720	1·65	„	30·3	176	127	29·4	69	58·6
10560	2·0	„	32·5	202	162	19	68	57·4

It will be observed that in all the above cases the equipment is not taxed to the limit of its capacity, and ample margin is allowed for making up time lost by slow-downs or signal checks. The hardest of the above schedules is the run of 5370 ft. at a schedule speed of 25·5 ml.p.h. Of course, with easier schedules the specific energy consumption would be lower, but the above may be considered as representative schedules for electric suburban services.

PART III.—ENERGY CONSUMPTION (ALTERNATING-CURRENT EQUIPMENTS)

The calculation of energy consumption with single-phase alternating-current equipments is more complicated than the above process, since the power-factor has to be taken into account. Moreover, the current during the period of initial acceleration is not controlled by rheostats, but by the application of definite voltages to the motor. The maximum variation of current during this period will, therefore, be dependent upon the number of controller notches. With motor-coach equipments five or six running notches are usually provided, but with locomotive equipments a much greater number (from 16 to 24) must be provided to enable the locomotive to accelerate heavy loads without slipping the driving wheels.

Generally the method of procedure will follow the lines indicated in the example below, but in some cases modifications may be adopted to simplify—and to shorten—the calculations.

Let us consider the motor-coach trains operating on the South London line (Victoria to London Bridge) of the London, Brighton and South Coast Railway. We will calculate the energy required for a run

of 4600 ft.—on level and straight track—at an average speed of 24·6 ml.p.h.

Certain data * of the trains and the equipment have already been given in Chapter XVI, while the characteristic curves of the motors are given in Fig. 74 (p. 96). A reference to this figure will show that the control provides for five running notches.

For the purpose of calculating the train resistance, we have assumed the cross-section of the coach body to be 82·5 sq. ft.; the total cross-section of the coach body and motors is assumed to be 94 sq. ft.; and the coefficient k , in equation (34), is assumed to be 0·95. The two

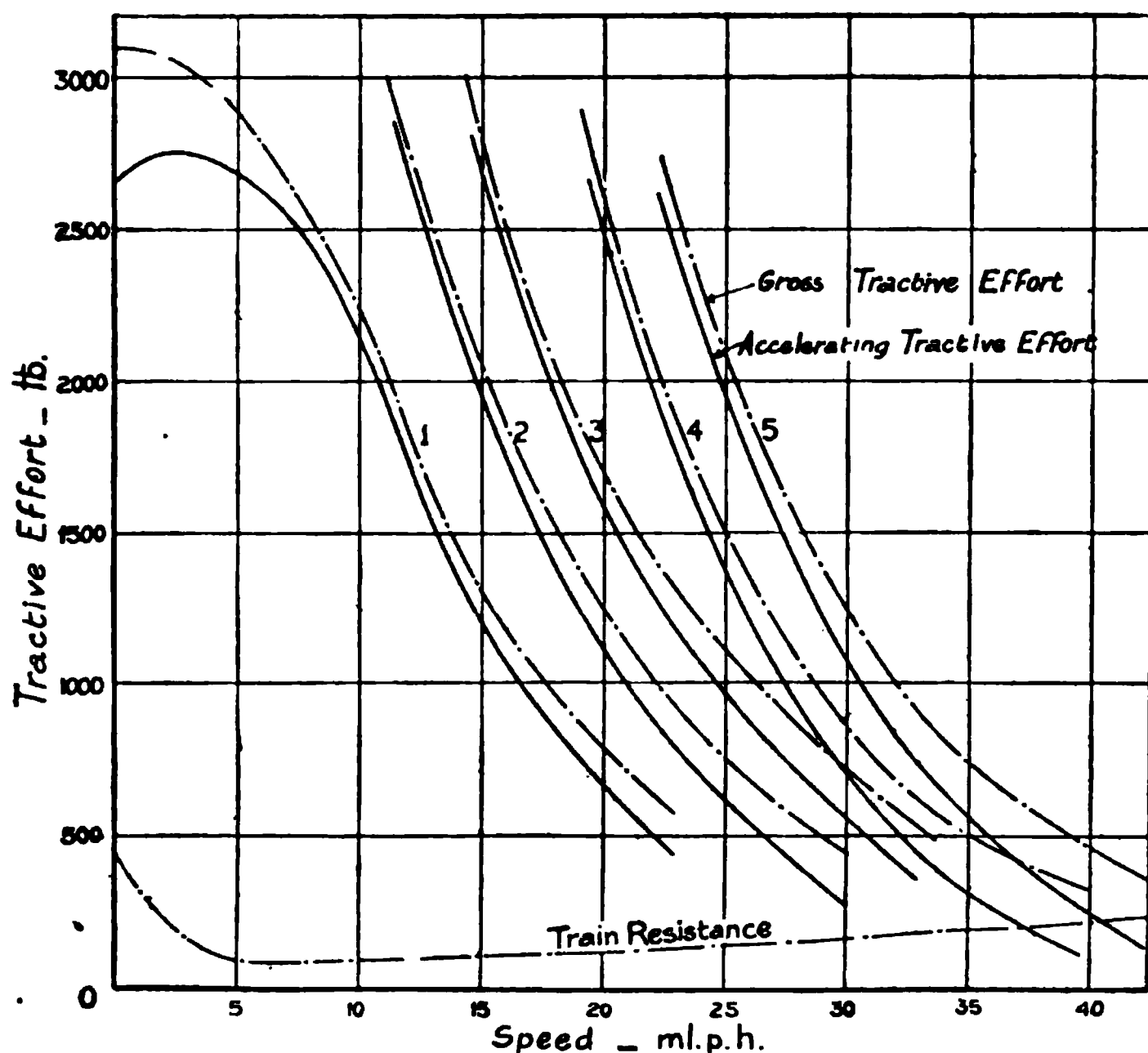


FIG. 369.—Curves connecting Speed and Accelerating Tractive-effort per Motor for Motor-coach Train with Single-phase (compensated repulsion) Motors.

motor-coaches are each 60 ft. long, while the two trailers are each 54 ft. long. The total seating capacity of a four-coach train is 284. Allowing for the full complement of passengers, we obtain—from the weights given on p. 19—the total weight of the train as 175 tons and the effective weight as 196 tons.

Adopting the general equation (38) for the train resistance of motor-coach trains, we obtain for the above four-coach train the equation $r = 4·1 + 0·055V + 0·00272V^2$. The values of the train resistance previously given on p. 427 (and in Fig. 356) can therefore be used in the present

* Complete data of the rolling stock and equipment are given by Mr. Philip Dawson in a paper entitled "The Electrification of a Portion of the Suburban System of the L.B. & S.C. Ry." (*Minutes of Proceedings of the Institution of Civil Engineers*, vol. 186, p. 29). See also *Engineering*, vol. 93, pp. 307, 548.

case. The apparent train resistance during coasting has been assumed to have the following values :—

Speed of train (ml.p.h.)	10	20	30	40
Apparent train resistance (lb. per ton)	10	12.2	14.8	17.5

The speed and tractive-effort curves of Fig. 74 must now be converted into curves of speed and accelerating tractive-effort as shown in Fig. 369.

We have now all the data necessary for the calculation of the speed-time curve and energy consumption. The speed-time curve is calculated

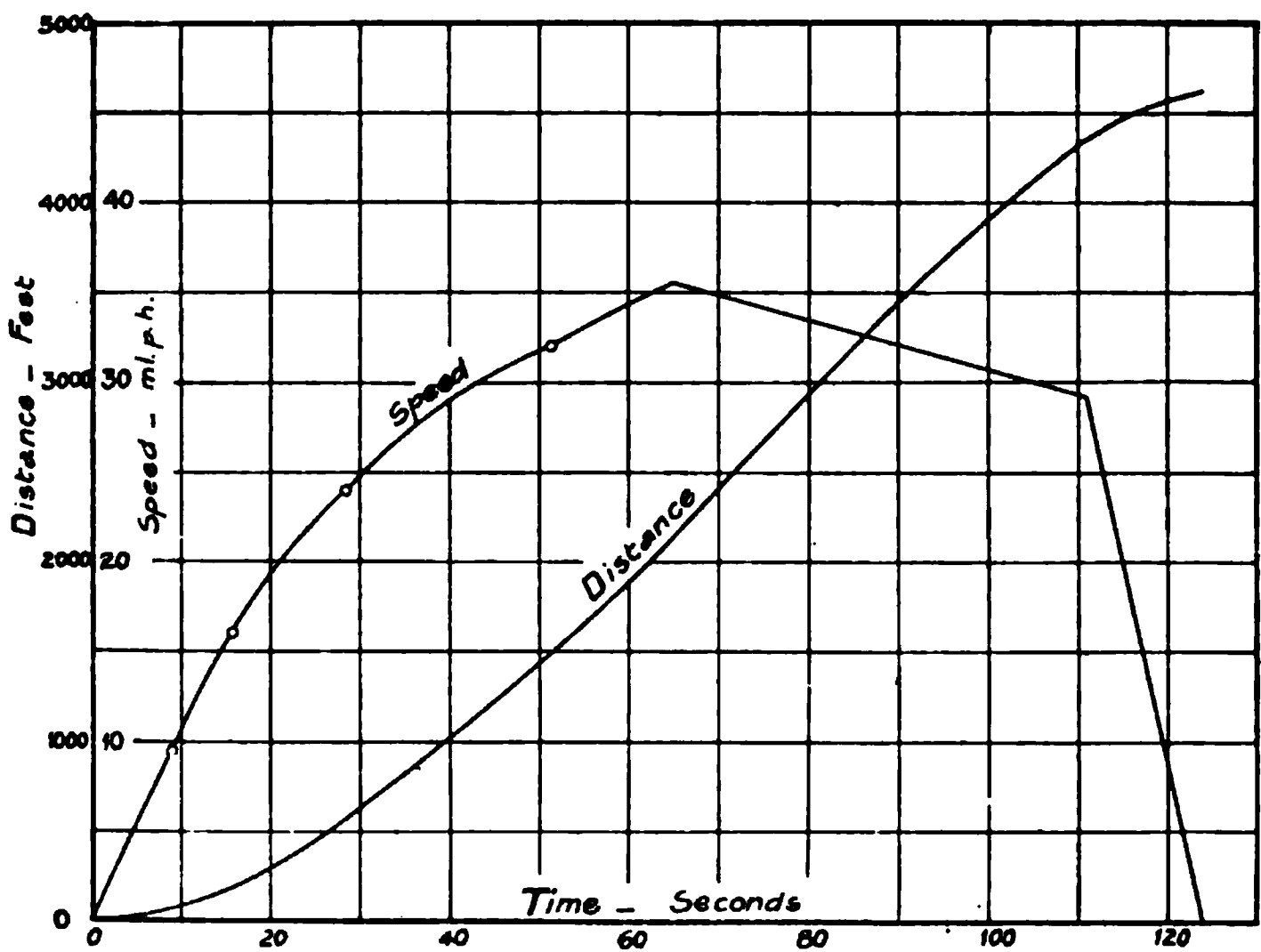


FIG. 370.—Speed-time Curve for Motor-coach Train with Single-phase Motors. NOTE.—The points marked o indicate a change of controller notch (4600 ft. run at 21.75 ml.p.h. schedule speed, 20-second stops).

by the above methods, except that, as the initial acceleration is variable, we must apply the increment process to this period as well as to the speed-curve-running period. The calculations for the energy consumption are carried through at the same time as those for the speed-time curve. Table XXI gives the various steps in the calculations.

The following points should be noted : (1) In starting the train, the controller is held on the first notch until the line current has fallen to a certain value, when a change is made to the second notch. The passage to the other notches is made in a similar manner. (2) The fifth (or last) notch is only used on long runs.

The speed-time and distance-time curves are given in Fig. 370, while curves of current, kw., power-factor, and efficiency are given in Fig. 371.

The energy consumption works out to 11.85 kw. per train mile, and the specific energy consumption is 67.4 watt-hours per ton mile.

Of the curves shown in Fig. 371, the efficiency curve is of particular

interest. This curve shows clearly that, although no rheostats are used during the starting period, the average efficiency is fairly low, while the average efficiency during the period of speed-curve-running is below 80 per cent. The low efficiency in the starting period is due to the low power-factor and the relatively large losses in the motors, and this point is frequently ignored in comparisons between single-phase and continuous-current equipments. Thus, comparing the efficiency curve given in Fig. 371 with that given in Fig. 367 for a gear

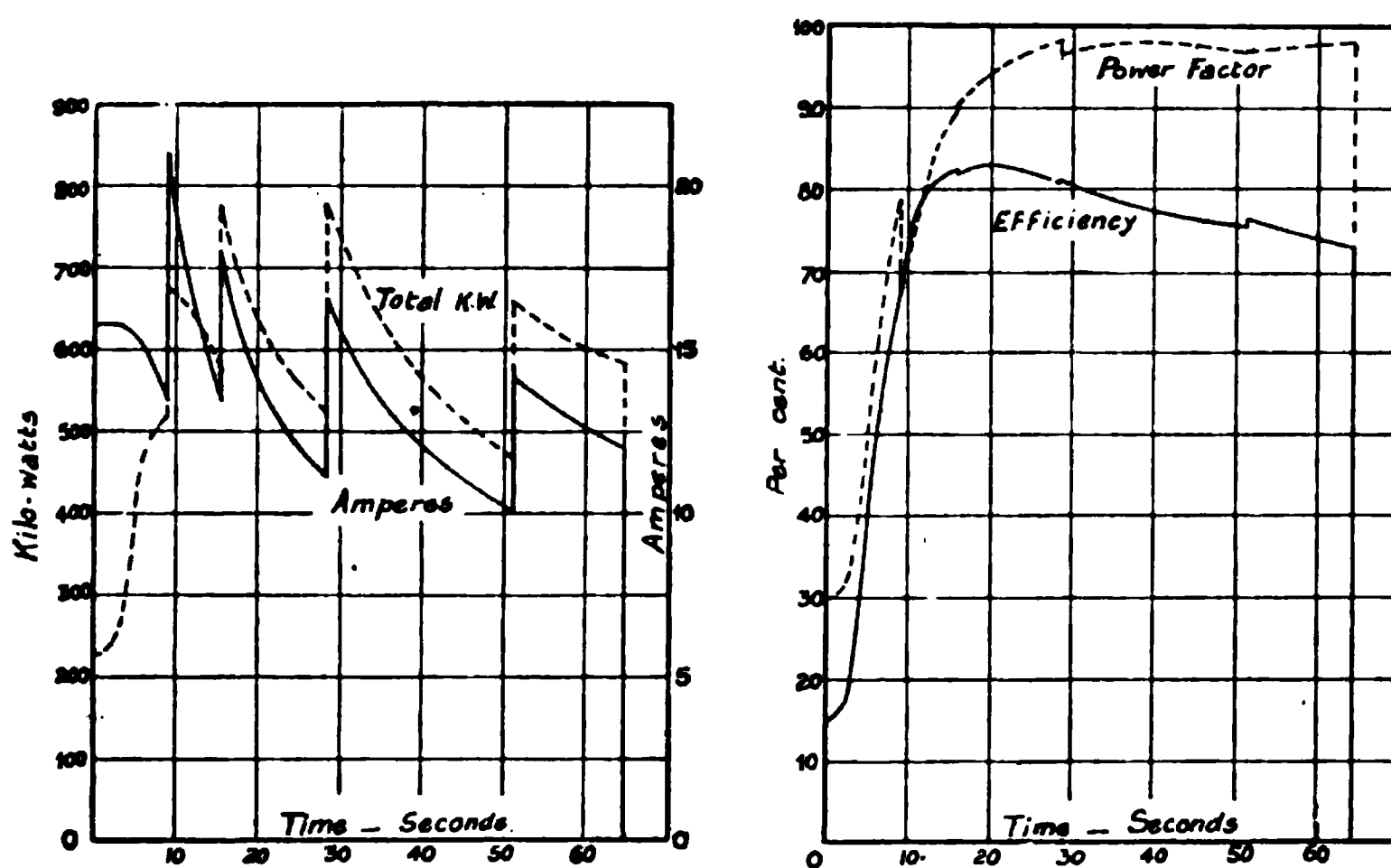


FIG. 371.—Current, Power, Efficiency, and Power-factor Curves for Motor-coach Train with Single-phase Motors.

ratio of 3.5, we find that, for the former case, the mean efficiency for the first 12.5 seconds is 47.3 per cent., while, in the latter case, the mean efficiency for the first 14 seconds (*i.e.* the period of rheostatic acceleration) is 52.6 per cent.

If the speed-time curve of Fig. 370 be compared with that in Fig. 358, the **effect of the sustained acceleration**, in Fig. 370, will be apparent. This sustained acceleration is a special feature of single-phase equipments, and is a result of the inherent characteristics of the motors and the method of voltage control. The feature is also possessed, though not to the same degree, by continuous-current equipments with field control (as will be apparent from an examination of the speed-time curves of Fig. 368).

TABLE

CALCULATION OF ENERGY CONSUMPTION FOR 175-TON FOUR-COACH TRAIN
BRAKING RETARDATION =

Controller Notch.	Speed.	Net Tractive- effort.	Speed Increment.	Mean Accelerating Tractive- effort.	Mean Acceleration.	Time Increment.	Time from Start.	Mean Speed.
	ml.p.h.	lb.	ml.p.h.	lb.	ml.p.h.p.s.	sec.	sec.	ml.p.h.
1	0	2660					0	
			3.75	2740†	1.095	3.42		1.875
1	3.75	2720					3.42	
			1.25	2700	1.08	1.15		4.37
1	5.0	2680					4.57	
			2.5	2690	1.04	2.4		6.25
1	7.5	2500					6.97	
			2.0	2365	0.98	2.05		8.5
1 } 2 }	9.5	{ 2220 } { 3470 }					9.02	
			1.5	3195	1.28	1.18		10.25
2	11.0	2920					10.2	
			1.5	2840	1.135	1.32		11.75
2	12.5	2540					11.5	
			3.5	2140	0.86	4.1		14.25
2 } 3 }	16.0	{ 1940 } { 2410 }					15.6	
			1.5	2215	0.89	1.7		16.75
3	17.5	2040					17.3	
			2.5	1795	0.72	3.5		18.75
3	20.0	1580					20.8	
			2.0	1435	0.57	3.5		21.0
3	22.0	1300					24.3	
			2.0	1185	0.48	4.2		23.0
3 } 4 }	24.0	{ 1070 } { 1540 }					28.5	
			2.0	1370	0.55	3.65		25.0
4	26.0	1200					32.1	
			2.0	1060	0.42	4.7		27.0
4	28.0	920					36.8	
			2.0	610	0.32	6.2		29.0
4	30.0	690					43.0	
			2.0	735	0.24	8.2		31.0
4 } 5 }	32.0	{ 520 } { 830 }					51.2	
			2.0	565	0.29	6.8		33.0
5	34.0	640					58	
			1.5	580	0.23	6.7		34.75
5	35.5	520					64.7	
		Coasting			—0.134	46.3		32.35
	29.2	—		—	—2.25	13	111	
	0	Braking					124	
		—						14.6

Kw. hours per train mile = $\frac{4614}{3600} \times 8 \times \frac{5280}{4600} = 11.8.$

† Average value obtained from Fig. 369.

WITH SINGLE-PHASE COMPENSATED-REPULSION-MOTOR EQUIPMENTS
2.25 ML.P.H.P.S.

Distance Increment.	Total Distance.	Ampere per Motor.*	Mean Ampere per Motor.*	Power Factor.*	Mean Power Factor.*	Mean kw. Input per Motor.*	Mean Energy Input per Motor.*
ft.	ft.						Kw. sec.
11	0	15.8	15.8	0.29			
7.4	11	15.8	15.7	0.35	0.32	30.3	104
22	18.4	15.6	15.2	0.45	0.4	37.7	43.3
25.5	40.4	14.8	14.15	0.68	0.57	52.0	125
					0.74	63	129
17.6	65.9	{ 13.5 } { 21.1 }	20	{ 0.79 } { 0.665 }			
22.8	83.5	18.9	17.9	0.745	0.7	84	98.7
85.4	106.3	16.9	15.15	0.79	0.77	82.7	109.3
					0.84	76.3	313
41.4	191.7	{ 13.4 } { 17.9 }	16.95	{ 0.895 } { 0.90 }			
95.7	233	16	14.8	0.92	0.91	92.6	156
107	329	13.6	12.85	0.95	0.935	83	289
142.5	436	12.1	11.6	0.97	0.96	74	258
					0.975	67.9	287
133.8	578	{ 11.1 } { 16.6 }	15.6	{ 0.98 } { 0.97 }			
187	712	14.6	13.75	0.975	0.972	91.3	333
262.5	899	12.8	12.15	0.978	0.977	80.7	381
323	1162	11.4	10.75	0.975	0.976	71.5	442
					0.973	62.9	515
329	1485	{ 10.1 } { 14.2 }	13.65	{ 0.972 } { 0.972 }			
340	1814	12.9	12.45	0.978	0.975	79.8	542
2200	2154	12		0.98	0.98	73.2	489
277	4354						
	4630						
Total							4614

Watt-hours per ton mile = $\frac{11.800}{175} = 67.4.$

* On high-tension side of transformer (at 6000 volts).

TABLE XXII.
DIMENSIONS OF BRITISH STANDARD SECTIONS. TRAMWAY RAILS, AND FISH-PLATES

TRAMWAY RAILS.											FISH-PLATES.		
B.S. Section.	Weight of Rail. lb. per yard).	Depth of Rail.	Width of Flange.	Thickness of Web.		Thickness of Flange.		Overall Width of Head and Check.	Width of Head at Tread.	Width of Groove at Top.	Depth of Groove.	Weight of Inner Plate.	Weight of Outer Plate.
				Top.	Bottom.	At Edge.	At Centre of Web.						
1	90	in. 6½	in. 6½	in. 1½	in. 1½	in. 2⅞	in. 3½	in. 3½	in. 1⅞	in. 1½	in. 1½	lb. 22½	lb. 27½
1c	96	"	"	"	"	"	3½	"	"	1½	1½	"	"
2	95	"	7	"	"	"	3⅞	1½	1½	1½	1½	22½	27
2c	101	"	"	"	"	"	4⅞	"	"	1½	1½	"	"
3	100	"	"	⅞	½	"	3½	"	2	1½	1½	22½	26½
3c	106	"	"	"	"	"	4⅞	"	"	1½	1½	"	"
4	105	7	"	"	"	"	3½	2½	2½	1½	1½	26	30½
4c	111	"	"	"	"	"	4⅞	"	"	1½	1½	"	"
5	110	"	"	"	"	⅞	3½	2½	2½	1½	1½	26	30½
5c	116	"	"	"	"	"	4⅞	"	"	1½	1½	"	"

NOTE : c denotes section for curved track.

The position of the web of the rail and the width of the base are such that the resultant of the forces, due to the weight of the car and lateral pressure of the wheel flanges, falls well within the base.

Rails of standard section may be obtained in lengths of 35, 45, or 60 ft. for straight track, and 35 ft. for curved track. The 45- or 60-ft. lengths are usually adopted on account of the reduced number of joints in the track.

Steel for tram rails may be made by either the Bessemer or the open-hearth process. When made by the **Bessemer process**, the chemical composition (recommended by the Engineering Standards Committee) is :—

Carbon	0.4 to 0.35 per cent.
Manganese	0.7 to 1.0 „ „
Silicon not to exceed	0.1 „ „
Phosphorus not to exceed	0.08 „ „
Sulphur not to exceed	0.08 „ „
Iron	98.64 to 98.19 „ „

while, for the **open-hearth process**, an average composition is :—

Carbon	0.65 per cent.
Manganese	0.8 „ „
Phosphorus	0.03 „ „
Silicon	0.14 „ „
Sulphur	0.03 „ „
Iron	98.35 „ „

The influence of the various constituents on the physical properties of rail steel can be stated thus :—

Carbon, manganese, phosphorus, and silicon have a tendency to harden. Manganese, in sufficient quantity, secures more uniform distribution of the carbon, and, in large quantities, gives extreme toughness and ability to resist abrasive wear. Steel containing a large proportion of manganese is practically non-magnetic, and has a much higher electrical resistance than ordinary steel. Silicon, in larger quantities than those given above, will cause the steel to be irregular and brittle after rolling. Phosphorus produces greater hardness than carbon or silicon, but results in “cold-shortness.” Sulphur has little effect on the tensile strength or ductility, but in excess of 0.08 per cent. gives seams and cracks in rolling, and also “hot-shortness.”

Where rails are liable to excessive wear, it is desirable to use a high-silicon steel, made by the **Sandberg process**,* having a composition as follows :—

Carbon	0.4 per cent.
Manganese	1.25 „ „
Silicon	0.3 „ „
Phosphorus	0.07 „ „
Sulphur	0.07 „ „
Iron	97.91 „ „

* See a paper by Mr. C. P. Sandberg on “The Chemical Composition of Steel Rails” (*Transactions of the Engineering Conference* (1907), section I, p. 6, *Institution of Civil Engineers*).

In the Sandberg process the silicon is introduced—in the form of high-percentage silico-spiegel—*after* the crude steel has been purified. By this method the brittleness due to high silicon is avoided, and the steel is dense, tough, hard, and fine grained. The rail wear with this steel has been found to be from 35 per cent. to 40 per cent. less than that with steel made by the Bessemer process.

The **fastenings** between individual rails may be made mechanically (by fish-plates), or the rails may be welded at the joints to form one continuous length. The **fish-plate joint** (see Fig. 372) consists of two curved plates—placed one on each side of the web of the rail—with inclined or “fishing” surfaces fitting between the head and flange of the rail, and bolted together with six bolts. It is essential that the fishing surfaces should be a good fit, since the life and strength of the joint is dependent on this condition. As the life of a rail is largely influenced by wear at the joint, and the latter is inaccessible for inspection and adjustment, the importance of good joints on a tramway track is very great.

FIG. 373.—“Continuous” Rail-joint.

A modification of the fish-plate joint is shown in Fig. 373, and is

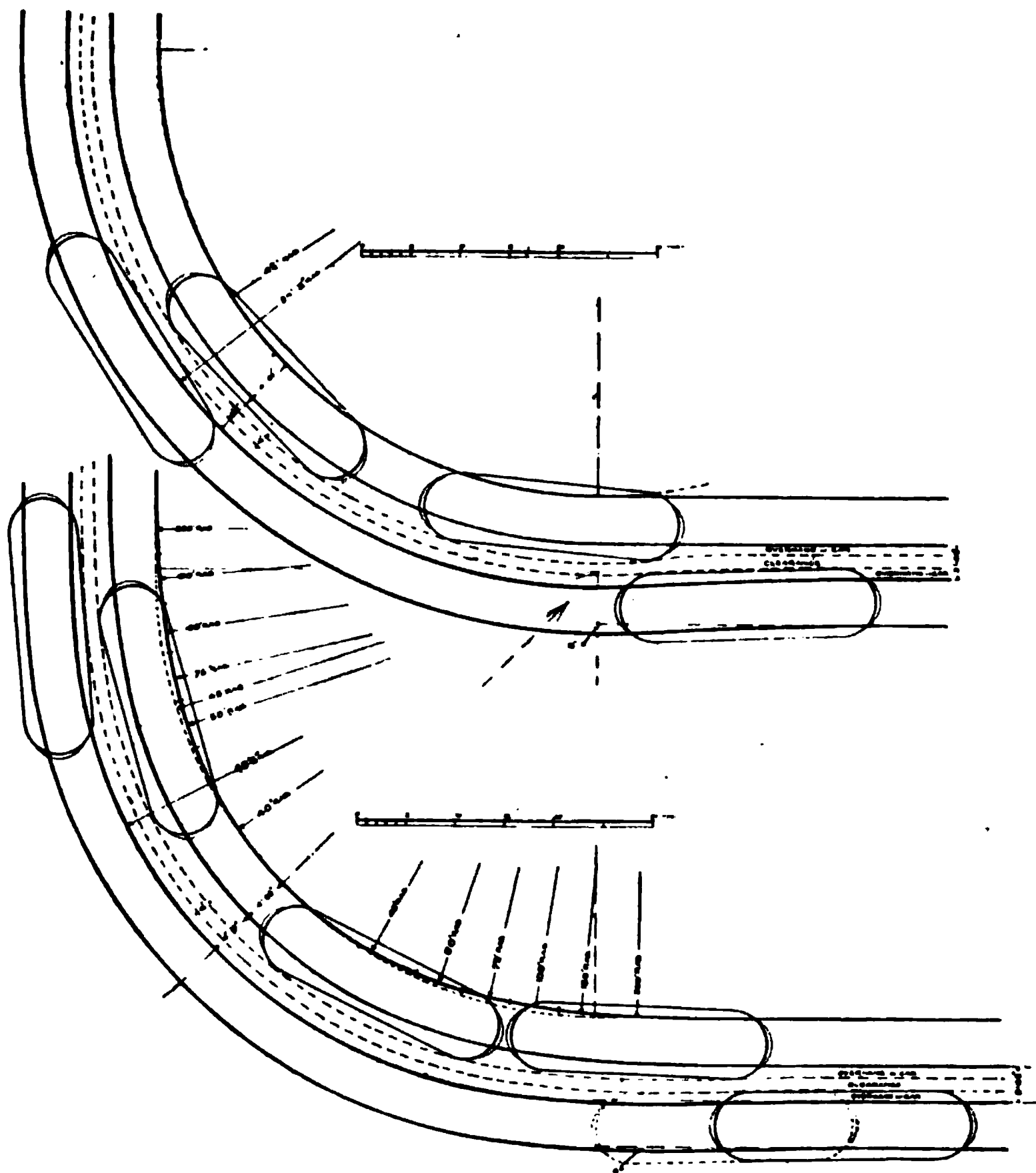
FIG. 374.—Thermit Rail-welding Outfit.

known as the **continuous rail-joint**. This joint provides larger bearing surfaces than the ordinary fish-plates, as well as greater vertical stiffness.

Where ordinary fish-plates are used, increased vertical stiffness can be obtained by bolting (across the joint) a short length of rail (inverted) to the underside of flange of track rail (see Fig. 398, p. 480). This method has been largely adopted, and it is also useful for anchoring purposes.

Welded joints are extensively used at the present day, as this method of jointing the rails provides a solution to track troubles due to faulty mechanical joints. The processes in use are the "Thermit," the oxy-acetylene, and the "Tudor." *

The **Thermit process** of rail-welding depends on the fact that aluminium, in a finely divided state and under certain conditions of



FIGS. 375, 376.—Layout of Double Track with Simple and Compound Curves (single-truck car, 6' 6" wheel-base).

temperature, is a powerful reducing agent. Thus, if a mixture of iron oxide (Fe_2O_3), flux, and finely divided aluminium is heated to about 2000°F. , an exothermic reaction takes place, producing a temperature of from 5000° to 6000°F. , and giving molten iron and aluminium oxide ($\text{Fe}_2\text{O}_3 + 2\text{Al} = 2\text{Fe} + \text{Al}_2\text{O}_3$). In the **practical application** of the Thermit

* See *Tramway and Railway World*, vol. 36, p. 128, for particulars of the systems of rail welding. (Paper by Mr. R. Humphries on "Rail Joints" presented to the Tramways and Light Railways Association (1914) Congress.)

process a powder, consisting principally of a mixture of finely divided aluminium and iron oxide, is ignited by a suitable ignition powder in a special crucible (Fig. 374). [The powder only requires to be ignited at one point for combustion to proceed throughout the whole mass without further supply of heat.] The crucible is arranged for tapping from the bottom, and the molten steel is run into a mould placed round the web and flange of rail. The rail ends and molten steel are thus fused together, and a butt weld at the rail head is obtained by tightening the clamps (Fig. 374) a few minutes after tapping the crucible. The mould is designed to give a band of metal, about 3 in. wide, round the joint, so that the strength is practically equal to that of the rail.

Trackwork at curves calls for special consideration where the radius is below 150 ft. In these cases the curve should be compounded with a spiral, in order to give an easier entrance, and to reduce the wear on wheel flanges and rails. With a spiral entrance the spreading of the

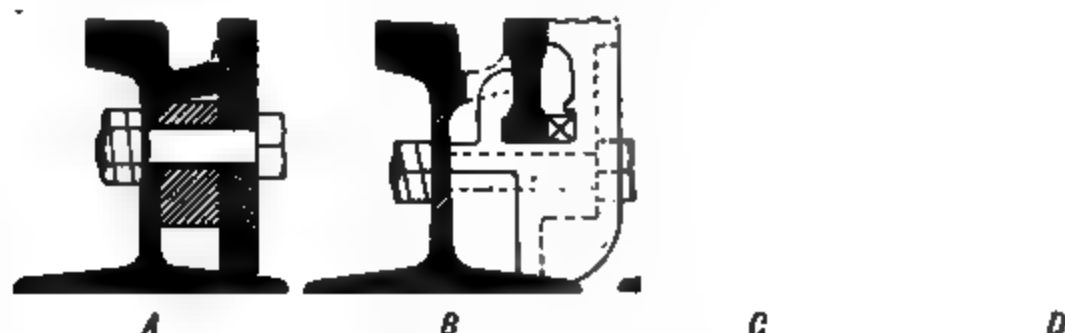


FIG. 377.—Types of Renewable Checks for Tramway Rails. A, Hadfields; B, Holt; C, London County Council; D, Bulfin.

track at the centre of the curve, to give the necessary Board of Trade clearance of 15 in. between passing cars, is less than that required for a curve of uniform radius. This is shown in Figs. 375, 376.

Where curves below 50-ft. radius are traversed by single-truck cars, considerable wear occurs on the check of the inner rail, due to the grinding action of the wheel flanges. In order to avoid having to renew a rail solely on account of a worn check, a modification of the standard rail with a renewable check has developed.*

The four types of renewable checks in use in this country are shown in Fig. 377. The Hadfields' type (A) consists of a rolled plate of "Era"† manganese steel. The Holt type (B) consists of a special check rail (of rolled manganese steel), which is keyed in chairs bolted to the web of the track rail. A rolled manganese steel check rail is adopted in the London County Council type (C), but in this case the check rail is bolted to the track rail, which is a special ("step") rail without a lip. In the Bulfin type (D) the check is made in sections (of cast manganese steel), which are bolted directly to the web of the track rail.

Points and crossings are required in connection with special track-

* Messrs. Hadfields manufacture rails for curves in *solid manganese steel*, which material is able to resist successfully the grinding action of the wheel flanges. It should be remarked that, on curves, the groove is worn at the check on the inner rail, and at the tread on the outer rail.

† "Era" (patent) manganese steel is a speciality of Messrs. Hadfields. The steel receives special heat treatment during manufacture: its chief properties are hardness, toughness, and ability to resist abrasive wear.

FIG. 378.—Hadfields' Open Tramway Point.

FIG. 379.—Hadfields' "Hecla" Tramway Point with Pinless Tongue

work, such as loops or turnouts (passing places for cars on single lines), cross-overs, junctions, &c.

Points can be divided into three classes, viz. (1) open or fixed points, sometimes called "mates"; (2) movable points; (3) automatic or spring points.

Open points have no tongues, and are used in conjunction with

Movable Point.

Automatic Pulling Point.

Automatic Pushing Point.

FIG. 380.

FIG. 381.

FIG. 381a.

Universal Operating Mechanism of Hadfields' "Hecla" Point. [The point can be arranged to act as either a movable point or an automatic point by changing the fulcrum of the rocking lever A.]

movable points, but in some cases a pair of open points (or "mates") are used under trailing conditions.

A **movable point** has a tongue which is operated either by a crowbar or through levers from the side of track. This class of point is used at turnouts, cross-overs, and junctions.

An **automatic point** has a tongue which is spring controlled, and is operated by the flanges of the car wheels. The tongue is kept in position for one direction of traffic by a spring, and is therefore self-setting when operated as a trailing point by a car coming from the other direction.

All points are made of manganese steel, with the tongues and grooves shaped to standard radii (100, 150, 200, 300, and 350 ft.). The overall

length may be from 10 ft. to 15 ft. 6 in., with tongues from 7 ft. 6 in. to 10 ft. long. Illustrations of typical modern points are given in Figs. 378, 379.*

Fig. 378 illustrates a **standard open point**. This class of point usually consists of a single casting of "Era" manganese steel.

Hadfields' universal spring point (which may be used either as an automatic point or a movable point) is shown in Fig. 379, while the universal operating mechanism is shown in detail in Figs. 380, 381. This mechanism consists of a spring plunger combined with a rocking lever to which the tongue of the point is mechanically connected. The fulcrum of the rocking lever is adjustable, and may occupy three posi-

FIG. 382.—Detail of Hadfields' "Hecla" Point, showing Adjustable Bearing at Heel of Tongue.

tions, viz. a central position, and a position on each side of the central one. In the central position—shown in Fig. 380—the movement of the tongue throws the rocking lever over the dead centre, so that the tongue does not return to its initial position. The point therefore performs the functions of a *movable point*.

When the fulcrum of the rocking lever occupies either the right or left position, the movement of the tongue cannot force the rocking lever over the dead centre, consequently the tongue returns to its initial position. The point therefore performs the function of an *automatic point*.

With the fulcrum in the right-hand position—as shown in Fig. 381—the tongue is pulled over towards the tread of the rail, while, with the fulcrum in the left-hand position, the tongue is pushed over towards the check of the rail. Thus, by altering the position of the fulcrum of

* The author is indebted to Messrs. Hadfields for the illustrations of points and crossings in this chapter and in Chapter XXI.

the rocking lever, the point may be converted into (1) an automatic pushing point, (2) a movable point, (3) an automatic pulling point.

The point illustrated in Fig. 379 has other special features in addition to the universal operating mechanism. Thus the body of the point and

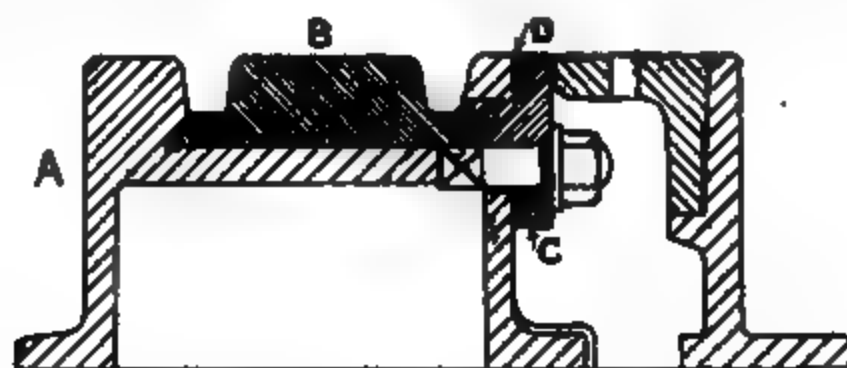


FIG. 383. Cross-section of Hadfields' "Hecla" Point at Heel. *A*, point body; *B*, tongue; *C*, adjustable wedge block; *D*, brass packing pieces.

the tongue are made of "Era" manganese steel, while the tongue is of the "pinless" variety. Detail illustrations of the **pinless hinge joint** are given in Figs. 382, 383. The heel (or hinge) end of the tongue fits into a dovetail recess in the body of the point, and is maintained in its correct position by an adjustable block (*C*, Fig. 383), the adjustment being

FIG. 384.—Early Tramway Point with Pin-bearing Tongue.

obtained by brass packing pieces (*D*, Fig. 383). The dovetail recess in the body, and the heel of the tongue, are both ground to give a perfectly fitting joint, while the whole of the underside of the tongue, and the bed (in the body) on which the tongue moves, are also ground to true surfaces.

This type of pinless tongue is a considerable improvement on the earlier type, in which the hinge was formed by a pin on the underside

FIG. 385.—Hadfields' Solid Tramway Crossing.

FIG. 386.—Hadfields' Solid "Unbroken Main-line" Tramway Crossing.

of the tongue working in a bearing bush in the body of the point (see Fig. 384). The advantages of the pinless-tongue point will be apparent from a comparison of Figs. 383, 384.

Crossings are usually made of manganese steel, and, for turnouts and cross-overs, are standardised with angles from 1 in $4\frac{1}{2}$ to 1 in 8, and lengths varying from 7 ft. to 11 ft. A typical standard crossing is illustrated in Fig. 385.

With crossings over which the traffic is principally in one direction, the **unbroken main-line** type—illustrated in Fig. 386—is preferable to the standard type, as the jolting of the cars in normal service is thereby avoided. The applications of points and crossings to special track-work are shown in the diagrams of Fig. 387.

Each end of a **turnout** requires one crossing, one open point, and one automatic point.

Each end of a **single junction** or **cross-over** requires one crossing, and either a pair of movable points or a pair consisting of a movable point and an open mate.

A **double junction** or **double cross-over** requires four pairs of points and eight crossings, the points being of either the movable or

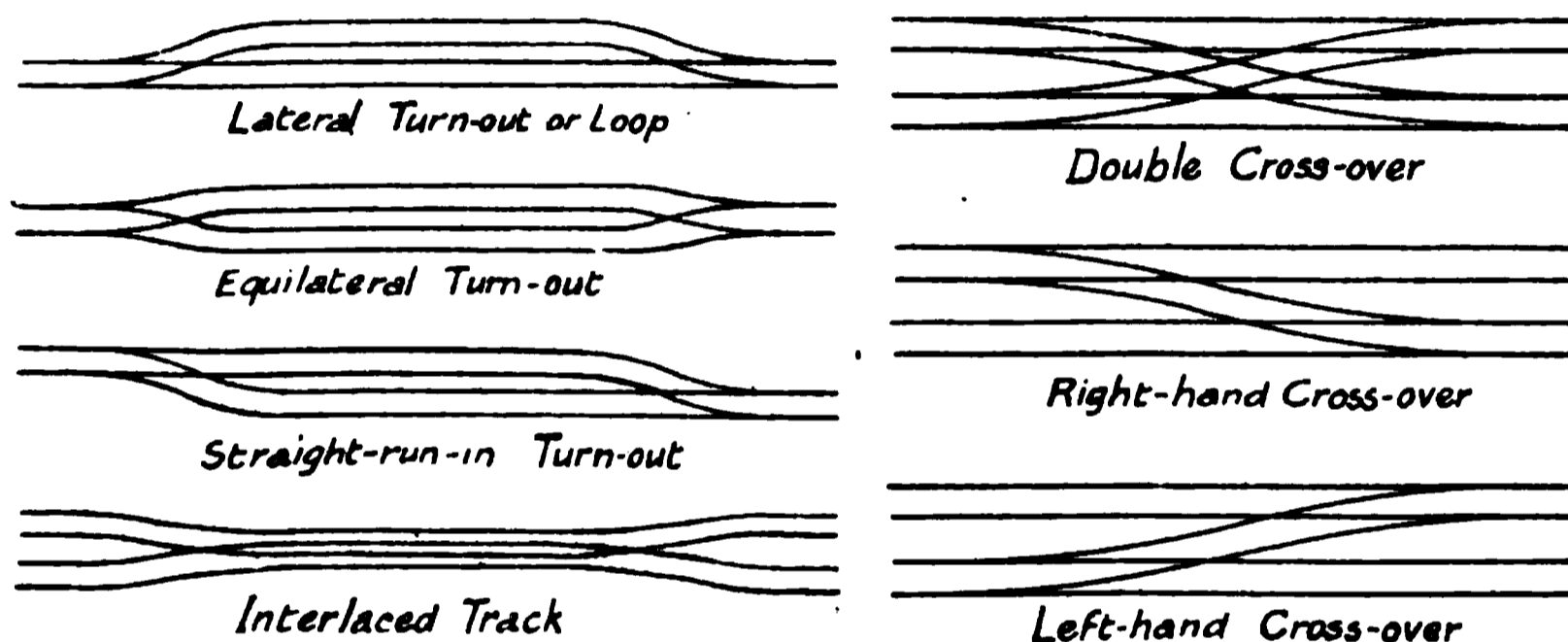


FIG. 387.—Examples of "Special" Track-work.

automatic types for facing or trailing positions. Alternatively, movable points and open mates—arranged in pairs—may be used.

Interlaced track requires only a crossing at each end. This form of special track-work is used at places (on a line of double track) where there is insufficient room for double track, and it possesses advantages over the use of single track at those places. Thus, points are not required, while the wear on the rails is uniform throughout the sections of double track and interlaced track. A practical example of interlaced track is illustrated in Fig. 388.

Electrically-operated Points.—At junctions in busy thoroughfares it is desirable to operate the points without manual labour. This can be arranged without difficulty on overhead systems. For example, the tongue of the point may be operated by an electro-magnet which is excited by the line current from a special overhead fitting in advance of the junction. If the point is required to be operated, the motorman keeps the controller in the first power position when passing this contact, while, if the car is to run through, the controller is kept "off." *

* See *Journal of the Institution of Electrical Engineers*, vols. 35 (p. 587). 44 (p. 470), for details of the Tierney-Malone electrically-operated point-shifter.

The **gauge** of the track is influenced by the width of the road and the type of car adopted. Where the conditions permit, it is desirable to adopt standard gauge (4 ft. 8½ in.), on account of the increased passenger accommodation on the cars. In the United Kingdom the following gauges are in use for tramways: 3 ft. 6 in., 4 ft. 0 in., 4 ft. 7½ in., 4 ft. 8½ in. (standard), 5 ft. 3 in.

The distance between the centres of adjacent tracks on the straight

FIG. 388.—Interlacing of Tracks at Double-track
Junction (Track-work by Hadfields).

must be such that a minimum clearance of 15 in. is obtained between cars when passing each other (see Board of Trade Regulations, p. 633).

The **foundation** for the track usually consists of 6 : 1 concrete, not less than 6 in. thick. In laying the track, the rails are supported on temporary packing and adjusted to the correct gauge by tie bars bolted to the web. The concrete is filled in to about 1 in. above the flanges of the rails, and the paving put down when the concrete has set.

CHAPTER XXI

TRACK CONSTRUCTION FOR CONDUIT TRAMWAYS

THE only examples in this country of electric tramways operating on the conduit system are in London (L.C.C. tramways) and Bournemouth. The London installation is of the centre-slot type, and at the present time (1916) comprises 122 miles of route (96 per cent. being double track) over the greater portion of which the traffic is exceptionally heavy.

On the other hand, the Bournemouth installation is principally of the side-slot type, and comprises about two miles of route through the centre of the town.

The **side-slot system** is somewhat less costly to instal than the centre-slot system, and has the advantage that no additional grooves (other than those in the track rails) are formed in the road surface, while the amount of exposed metal at the road surface is smaller than in the centre-slot system. Against these advantages, however, there are the following disadvantages: (1) the width of the side-slot at junctions is liable to become excessive; (2) the points are more complicated than those for the centre-slot system. Although the difficulties in connection with the points are not insurmountable, nevertheless, in many cases, the slot is deflected to the centre of the track to overcome the above objections.

The **present construction** of the **centre-slot system** on the L.C.C. tramways differs in many details from the original construction installed in 1903. In the original construction the slot-rails were fixed to cast-iron yokes (see Fig. 389), to which the track-rails were connected by tie-bars. The yokes were spaced 3 ft. 9 in. apart, and were embedded in concrete, with which the sides of the conduit were also formed. The T conductor-rails were carried from insulators, bolted to the flange of each slot-rail, as shown in Fig. 390, the insulators being accessible from the road surface by removable covers.

The principal features in which the modern construction differs from the original construction are: (1) the use of "extended" yokes; (2) the abandonment of removable covers over the insulators; (3) the use of a slot 1 in. wide instead of $\frac{3}{4}$ in. wide; (4) the increase in the width of the conduit to 16 in.

In addition, improvements have been introduced in the construction and drainage of the conduit, and welded joints are now extensively used on the track-rails.

The yokes are now of two patterns, the "**extended**" yoke (Fig. 391) and the "**short**" yoke (Fig. 389), the former weighing 400 lb. and

the latter 200 lb. The extended yokes support the track-rails in addition to the slot-rails, and are spaced 7 ft. 6 in. apart, while the short yokes support the slot-rails only, and are placed midway between the



FIG. 389.—L.C.C. Conduit Tramways (1903 construction). Cross-section of Track at Yoke.

extended yokes. A view of the track construction in progress, showing the yokes, rails, and tie-bars, is shown in Fig. 392. It will be seen that the slot-rails, in addition to being tied to the short yokes, are tied

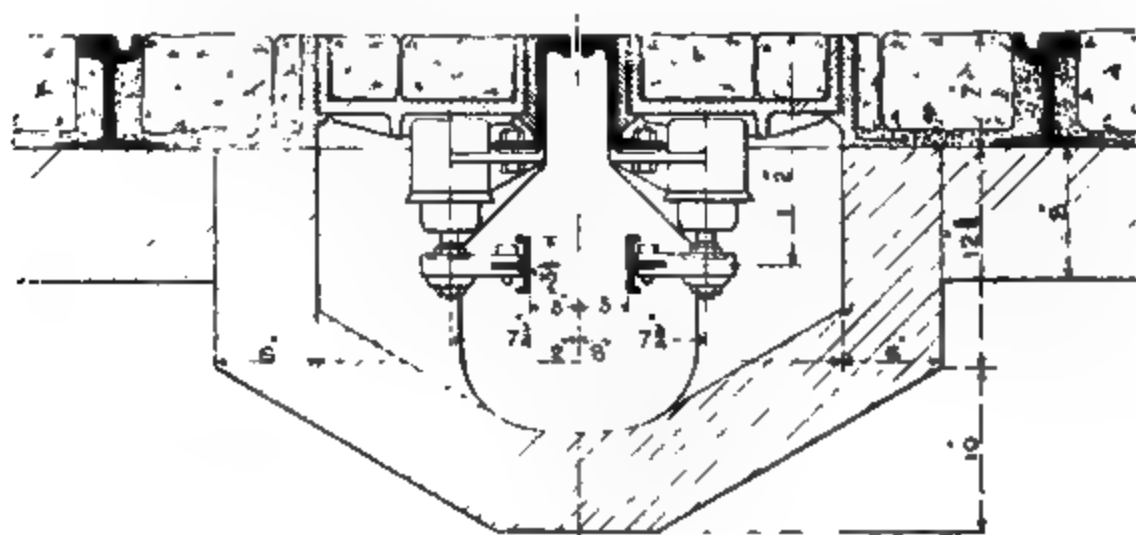


FIG. 390 --L.C.C. Conduit Tramways (1903 construction). Cross-section of Track at Insulator Pocket.

to the track-rails at each extended yoke, while the gauge of the track-rails is adjusted by taper keys. A reference to Fig. 391 will show that a hardwood packing strip ($\frac{1}{8}$ in. thick) is inserted between the flange of each track-rail and the yoke. The joints in the slot-rails are arranged at the centre of a yoke (see Fig. 392), thereby rendering joint-plates

unnecessary. Where the joints in the track-rails are not welded, the ordinary fish-plate joint, supplemented by a sole-plate consisting of a short length of inverted rail (see Fig. 398, p. 480), is adopted.

After the track-rails have been lined up and levelled, the yokes are set in 6 to 1 concrete. The centering (*A*, Fig. 393)—by means of which the correct shape is given to the conduit—is next placed in position between the yokes, after which the paving strips *B* and boxes *C* (for the insulator pockets) are fixed, as shown in Fig. 393. The temporary packing blocks under the track-rails (see Fig. 393, left-hand track) are then removed, and the space up to the flanges of the rails is filled with 6 to 1 concrete.

The **centering** was originally constructed of wood, but on straight track a collapsible sheet-iron centering is now used. This is constructed in lengths 3 ft. 9 in. long, and consists of two sheets, hinged together

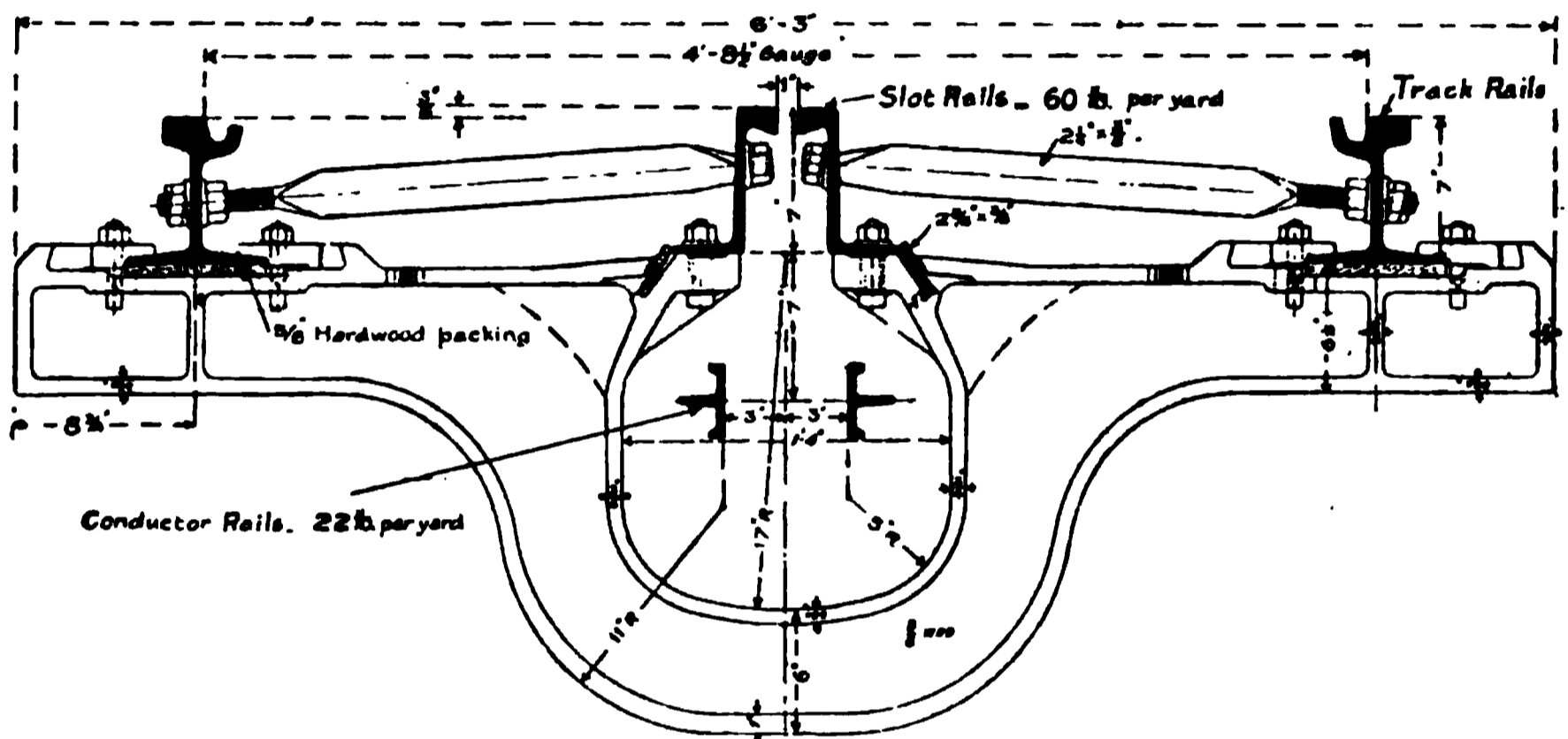


FIG. 391.—Extended Yoke, L.C.C. Conduit Tramways. [Track rails: B.S. Section No. 4—105 lb. per yard.]

at the bottom, and pressed against the yokes by toggle joints at each end. When the concrete has set, the centering can be made to collapse, and can be extracted through openings which have been left for that purpose. At special track-work the wooden type of centering is used, and a portion of this is shown lying by the track in Fig. 393.

The **paving strips** *B* (Fig. 393), which consist of lengths of $2\frac{1}{4}$ in. by $\frac{3}{8}$ in. wrought iron fitting in grooves in the yokes, are for the purpose of preventing the concrete next to the flange of the slot-rail from breaking away.

The **insulator pockets** are placed 15 ft. apart, and the insulators are bolted to the flanges of the slot-rails, as shown in Figs. 394, 396. Details of the insulators are given in Fig. 394.

Each insulator pocket is covered by a cast-iron plate (Fig. 395), which is supported partly on the flange of the slot-rail and partly on the concrete, and is finally cemented in position. In order to indicate the position of these covers on the road surface, a special square sett or block is placed over each when the paving is laid. With this construction a faulty insulator is accessible only after the paving and the

FIG. 392.—Track Construction in Progress, showing Yokes, Rails, and Tie-bars in Position.

FIG. 393.—Track Construction in Progress, showing Centering in Position.

cover-plate have been removed. This feature is not considered to be a disadvantage in practice, for, in the first place, the insulators are very reliable; and, secondly, the sealing up of the insulator pocket prevents the ingress of mud, &c., which was found to occur when the removable boxes were used.*

In renewing the original track, the removable covers are replaced by the modern non-removable covers illustrated in Fig. 395.

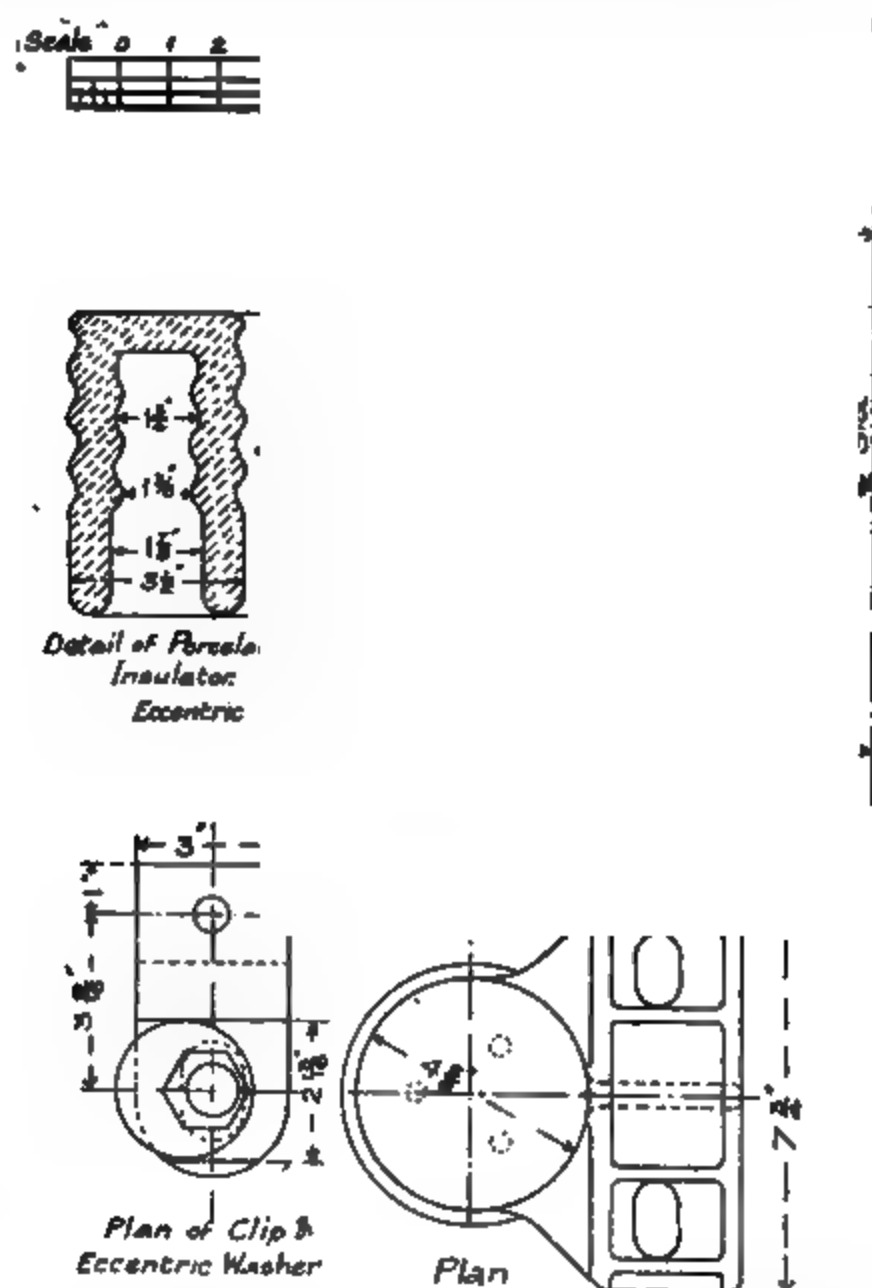


FIG. 394.—Details of Insulator for Conduit Tramways.

The conductor rails are of "T" section, weighing 22 lb. per yard, and consist of high conductivity steel, having a specific resistance of 4.25 microhms per inch cube. The dimensions are shown in Fig. 394.

At each insulator the rail is held in a clip (Fig. 394), which is

* In this connection the following paragraph from Rider's *Electric Traction* (Whittaker & Co., 1903) is of interest: "On some of the Continental lines, notably in Paris and Berlin, the insulator boxes are kept well below the surface of the road, and the paving is carried right over them. The engineers in charge of those lines say that they seldom have to inspect any of the insulators, and that, when they do, it is preferable to break up the paving at that point, than to be troubled with flush road boxes all the time. Certainly the appearance of a road without the boxes is much superior to a road with them."

bolted to the insulator pin, the rail being adjusted to the correct position by means of an eccentric washer, working in a groove in the clip. A double clip is used at the joints, and each joint is bonded with two flexible bonds having $\frac{7}{8}$ -in. terminals expanded into the rails. The clip, eccentric washer, and bonds can be seen in Fig. 396, which shows the insulator and conductor-rail in position in the conduit.

Section insulators, consisting of a 2-ft. gap in the conductor-rails, are placed at intervals of half a mile, at which points cables are connected to the feeder pillars and substation. (See Chapter XXVI for details of these pillars.) Each end of the conductor-rail is flared back $1\frac{1}{2}$ in. in order to prevent the shoes of the plough from fouling, and at these points each rail is supported by two insulators arranged as in Fig. 397.

FIG. 395.—Insulator Cover Plates.

A "plough hatch" or "plough box" is usually fitted in the slot-rails at each section insulator. (See Fig. 397.) This consists of two removable plates, each about 3 ft. long by 4 in. wide, which, when removed,

FIG. 396. —Insulator and Conductor-rail in position in Conduit.
A, double clip; B, eccentric washer; C, conductor-rail; D, bonds; E, insulator; F, slot-rail.

leave a fairly large opening over the conduit, through which a plough can be withdrawn.

Special Work.—In conduit tramways the track-work at cross-overs and junctions is considerably more complicated and costly than that

at similar places on tramways operating on the overhead system, since not only must a clear passage be provided under the roadway for the plough, but special points are required for the slot-rails as well as for the track-rails. The amount of exposed metal at the road surface will, therefore, be considerable, while the amount of metal below the road surface will be still greater, on account of the extra yokes and gussets which are required for supporting the special work.

The nature of the special work for a double-track crossing is shown

†

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Sectional Plan, showing
Section Insulator and
Cable Connections.

Plan, showing Yokes,
Plough Box, and In-
sulator Cover-plates

FIG. 397.—Section Insulator and Plough Box (L.C.C. Tramways). NOTE.—The cable ducts from conduits to feeder pillar are shown in dotted lines.

in Fig. 398, while the special work for a cross-over is shown in Fig. 399. These illustrations refer to track-work for the L.C.C. tramways, and show this work assembled on the lay-out floor at Messrs. Hadfields' works. Only the special work is shown assembled, the standard yokes and other fittings being omitted.

The points, crossings, and other parts subjected to wear are constructed of manganese steel, while the remaining portion (with the exception of the rails and fastenings) is of cast steel. It will be observed that the points in the slot-rails are placed after those in the track-rails, so that the car will be on the correct road before the plough meets the points.

FIG. 398.—Special Track-work for Double-track Crossing (London County Council Conduit Tramways). Attention may be directed to the complicated nature of the manganese steel castings required for special track-work of the type illustrated above and in Fig. 399.

FIG. 399.—Special Track-work for Left-hand Cross-over (London County Council Conduit Tramways).

The **points for the slot-rails** are of a special design, and are shown in detail in Fig. 400. Each slot-point consists of two leaf tongues, which move under protecting covers, the latter being flush with the road surface. The tongues are operated, through suitable mechanism, by a lever inserted in a slot at the side of the track. (In Fig. 400 the covers have been removed, thus exposing the tongues and operating mechanism.) In the straight-run-through position one leaf tongue guides the plough past the throat of the point, while in the branch position this tongue moves under its cover-plate, and the other leaf tongue moves out to guide the plough to the branch track.

In order to provide a clear passage for the plough in each direction,

FIG. 400.—Hadfields' Centre-slot Point for Conduit Tramways.
View with protecting covers removed, showing leaf tongues
and operating mechanism.

it is necessary to insert long breaks—amounting to 12 ft. or more—in the conductor rails, the disposition of the latter being indicated in Fig. 401. At important junctions the various sections of the conductor rails are connected to switches in feeder pillars, and in other cases they are interconnected by jumper cables laid in suitable ducts.

The **twin-slot** is another example of special work which has been adopted in some parts of London where the road is not wide enough for double track. In this case a single pair of track-rails is provided with two conduits, thereby avoiding the complication of slot-points.

Drainage.—It is very important that efficient means be adopted for preventing any accumulation of surface water or mud in the conduit. The following method is adopted in London. The track-rails are drained by drain boxes, connected to the conduit through 3-in. pipes. (These drain boxes can be seen in Fig. 393.) The conduits are drained into sump pits, spaced at intervals of 120 ft. along the track, the pits being constructed of concrete and placed in the clearway between

the tracks. Each sump pit has a maximum depth of 7 ft. 9 in., the catch-pit being 3 ft. 6 in. deep by 3 ft. by 2 ft. The upper portion of the pit extends the full width between the conduits, which terminate at each wall. In this manner a depositing bench—for mud from the conduits—is formed. The removal of the mud and the flushing of the pit is performed periodically. The catch-pit is connected to the sewer by a 9-in. pipe, the sill of which is 2 ft. 5 in. above the bottom of the pit. The mouth of the pipe is provided with an iron hood arranged to give a water seal 5 in. deep.

It is, of course, necessary to provide means for withdrawing any mud from the bottom of the conduits into the sump pits, as the natural drainage cannot be relied upon to do this effectually unless the road is on a gradient. A scraper is used for this purpose, and is either manually operated or drawn through the conduit on a special framework attached to a car.

The Side-slot Conduit System.—We shall now consider briefly the side-slot system, as installed in Bournemouth, and show the prin-

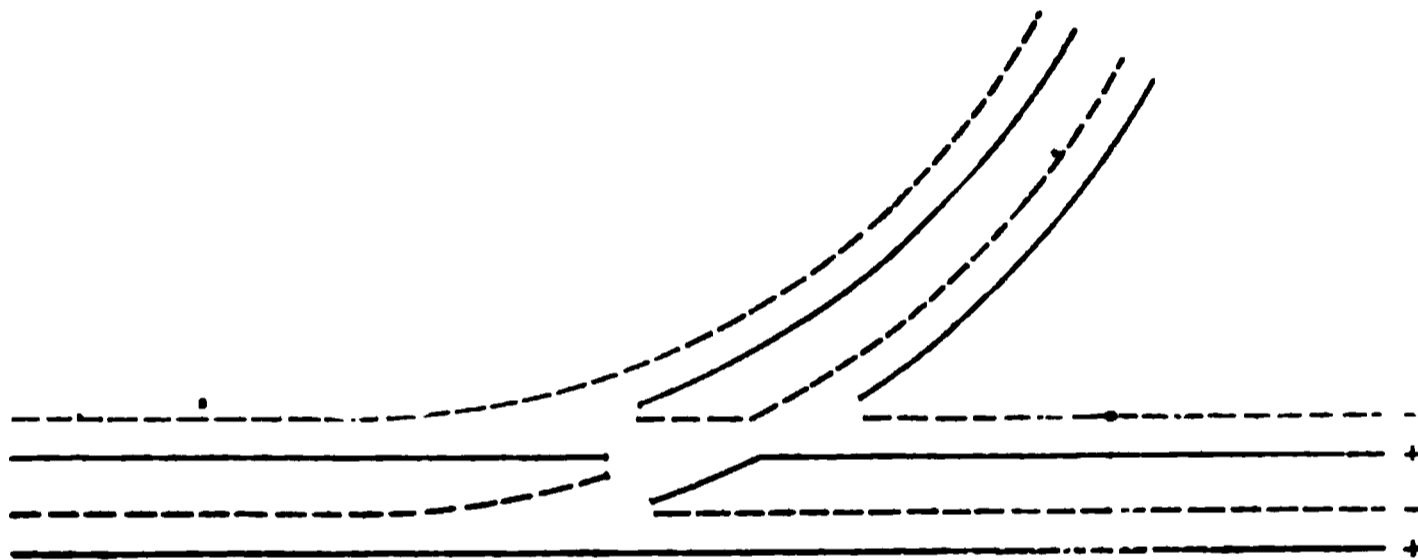


FIG. 401.—Arrangement of Conductor Rails at Double-track Junction.

incipal points of difference between the construction for this system and that for the above centre-slot system. There are, however, several points of similarity in the two installations, as the same contractors (Messrs. J. G. White & Co.) installed both the Bournemouth and the original L.C.C. lines. Thus the type of insulator, the section of the conductor rails, and the method of mounting and fixing these, are the same in each case, while the yokes are of similar design.

The slot, for the greater portion of the Bournemouth installation, takes the place of the groove in one of the track-rails, and accommodates the flanges of one set of wheels in addition to the plough. The width of the slot is 1 in., this being the least permissible width for standard $\frac{3}{4}$ -in. wheel flanges, but at places where the slot is deflected to the centre of the track the width has been reduced to $\frac{1}{2}$ in.

The general construction of the conduit is shown in Fig. 402. The yokes are similar in design to the short yokes on the L.C.C. lines, but are stronger. They are spaced 3 ft. 9 in. apart, with the tie-bars arranged in a manner similar to those on the above system.

A drawing of one of the slot-rails and fish-plates is shown in Fig. 403, from which it will be seen that the rail is of a modified girder type, with a drip edge on the base. The fish-plates are of the continuous-joint

type (see p. 463), 2 ft. 1½ in. long, and a special fish-plate and bolt-head is used on the slot side of the rail. The outboard track-rail is of the

LONGITUDINAL SECTION



FIG. 402.—Details of Side-slot Conduit (Bournemouth).

standard grooved type, and is connected to the adjacent slot-rail by tie-bars spaced 7 ft. 6 in. apart and fixed between the yokes.

The insulators are spaced 15 ft. apart, and are covered with a plate below the paving.

The sump pits, which are of similar design to those described above, are spaced at intervals of about 40 yds., and are supplemented by cleaning pits, located at intervals of 120 ft. These cleaning pits consist of an enlarged insulator pocket, without insulators, and enable mud, &c., to be removed without having to transfer it to the sump.

The special feature of the Bournemouth installation is the deflection of the slot to the centre of the track at junctions, in order to avoid the large slot opening which usually results when a side-slot point is used. At some extensions of the system a special side-slot point,* in which the opening does not exceed the normal width of the slot, has been introduced. A view showing the special work at one of these side-slot points is given in Fig. 404.

The chief difficulty in the design of a side-slot point is that the tongue has to be supported so that it is capable of carrying the load due to a car passing over it. In the Connett design (Fig. 404) this difficulty is overcome by the use of two supporting tongues (which we will designate *A* and *B*) on opposite sides of the slot. These tongues are connected to a special yoke which is operated through a lever at the side of the track, this lever also controlling the tongue of the point. When the point is in one position, its tongue is supported by one of the above tongues (say *A*), the other (*B*) being clear, so as to provide an unobstructed path for the plough. In the other position of the point the support of the tongue is transferred to *B*, and *A* is moved clear. The operation of the movable tongues is somewhat similar to those on the centre-slot point described above, although, of course, the designs are quite different.

FIG. 403.—Slot-rail and Fish-plates for Side-slot Conduit System.

Combined Conduit and Overhead Trolley Systems.—On the Bournemouth installation, and also on some parts of the L.C.C. tramway system, the cars operate on both the conduit and overhead trolley systems. At the termini of the conduit system the plough must either be raised from the conduit, so as to clear the track, or removed from the truck. The former method is adopted in Bournemouth and the latter in London.

At each terminus in Bournemouth the slot is deflected to the centre of the track, and terminates in a plough pit 4 ft. long. The plough pit is provided with two movable covers, which are operated through levers from the side of the track. The covers open to a distance of 9½ in., through which the plough is raised by special lifting gear on the truck.

At the London termini the slot is deflected into the clearway between

* Designed by Mr. A. N. Connett, Chief Engineer to Messrs. J. G. White & Co.

the tracks, the conductor rails terminating a short distance previous to this deflection. The plough is run off the plough-carrier on to a small trolley by the combined motion of the car and the deflection of the slot,

FIG. 404.—Connett Side-slot Point (Bournemouth).

the weight of the plough during the transition period being taken on a special fork placed in the plough-carrier by a tracksmen. The plough, on its trolley, is then run into position for being placed on a car travelling in the opposite direction.

CHAPTER XXII

THE TRAMWAY TRACK CONSIDERED AS AN ELECTRICAL CONDUCTOR

In tramways operating on the overhead system the track rails, in conjunction with feeder cables, form the return conductor to the negative pole of the generators. It is necessary, therefore, to consider the electrical properties of the rails and track.

The **specific resistance** of steel, having the same composition as standard (E.S.C.) Bessemer tram-rails, averages 7·5 microhms per inch cube at a temperature of 20° C. The cross-sectional area and resistance per foot of standard rails are given in Table XXIII.

TABLE XXIII

CROSS-SECTIONAL AREAS AND RESISTANCE OF TRAMWAY RAILS

B.S. Section.	Lb. per Yard.	Cross-sectional Area.	Resistance per Foot of Rail.
		square inches.	microhms.
1	90	9·0	10
2	95	9·5	9·47
3	100	10·0	9·0
4	105	10·5	8·57
5	110	11·0	8·18

Thus, although the material of the rails has a moderately high specific resistance, the cross-sectional area of a rail is large, so that the resistance of a single track of *continuous* rails would not exceed 0·025 ohm per mile. The ordinary fish-plate joint, however, has a high resistance relative to the rail, and it is necessary, therefore, either to eliminate this type of joint from the track by welding the rails, or to supplement it with a good conductor or "bond," in order that the conductivity of the track may be maintained.

A **joint having a low resistance is necessary**, not only for reasons of economy, but on account of the Board of Trade regulations (p. 633), which limit the voltage drop in the rails to seven volts, and the voltage

between any pipe and the rails to one volt positive and three volts negative.

These regulations were made at a time when considerable trouble was being experienced (due to the corrosion of water and gas pipes and lead cable sheaths) by the stray currents resulting from imperfect bonding of the rail joints. The magnitude of this corrosion has been demonstrated by Mr. I. H. Farnham in a paper on "The Destructive Effect of Electric Currents on Subterranean Metal Pipes."* In this paper it is shown that the corrosion of the pipes was due to (a) the positive terminal of the generator being connected to the rails, and (b) imperfect bonding of the rail joints, so that the pipes acted as feeders to the rails. The current left the pipes for the rails at numerous points, and as each point, with the surrounding soil and rails, formed an electrolytic cell in which the pipe was the anode, the corrosion was considerable.

The methods adopted as a remedy for these troubles were: (1) to

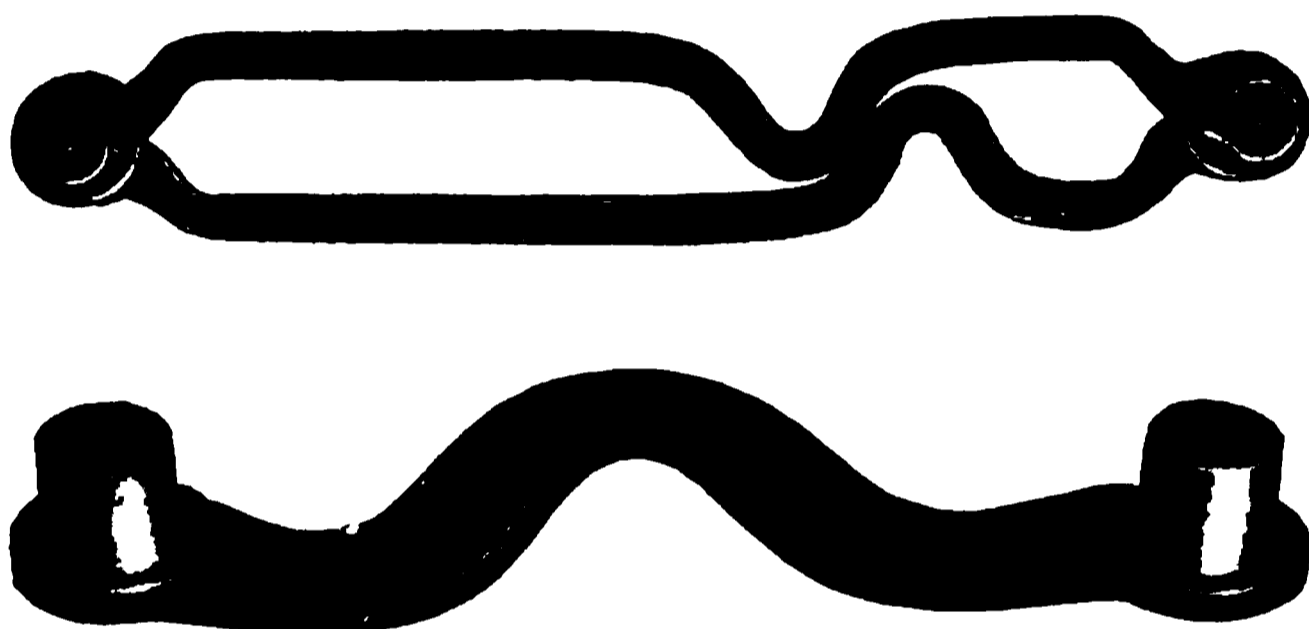


FIG. 405.—"Protected" (Ribbon-type) Bonds for Tramway Rails (British Insulated and Helsby Cables).

connect the negative terminal of the generator to the rails; (2) to bond the rail joints and cross-bond the rails; (3) to bond pipes to the rails when the former were in close proximity to the latter; (4) to lay cables from the negative bus-bar to the pipes which were positive to the rails under the new conditions, the object of the cables being to lead the current out of the pipes by a path of low resistance.

It is interesting to notice that the first three methods are incorporated in the Board of Trade regulations. The fourth method has been superseded by the more satisfactory method of limiting the voltage drop in the rails, since this tends to prevent leakage currents, and is obviously more logical than endeavouring to prevent troubles arising from leakage currents.

In order to maintain the voltage drop in the rails within the limit of seven volts, it will generally be necessary to instal "negative" feeders, i.e. cables connecting various points of the rails to the negative bus-bar (see Chapter XXVI). With a properly designed negative feeder system and the voltage drop in the rails within the above limit, there are practically no corrosion troubles, even on extensive tramway systems.†

The bonds in general use for tramway rails can be divided into two

* *Transactions of American Institute of Electrical Engineers*, vol. 11, p. 191.

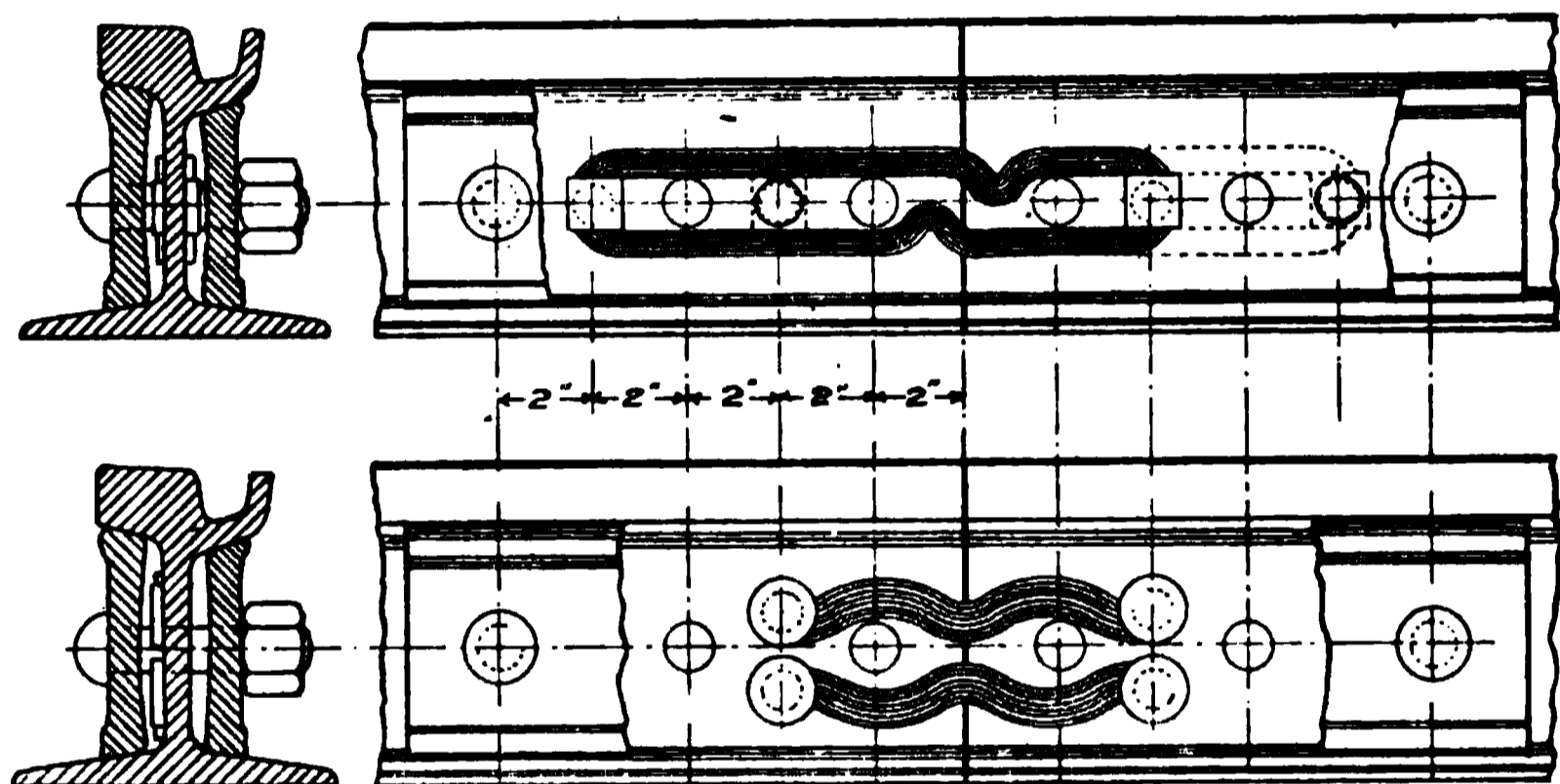
† See *Journal of the Institution of Electrical Engineers*, vol. 43, p. 464.

classes, according to the method of fixing the terminal of the bond into the rail. Each class can be subdivided into two groups, according to whether the bond is placed outside the fish-plates or between the fish-plates and the web of rail.

Formerly all bonds were fixed into the rail by driving a drift-pin into a hole passing through the terminal head. This expanded the terminal into the hole in the rail, but the pressure obtained by this process was not sufficient to maintain a low contact resistance under all conditions.

Modern bonds have solid terminal heads, which are fixed in position under considerable pressure, so that a low contact resistance is obtained under all conditions.

One type of solid bond (known as the Columbia bond) consists of a copper rod, with each end in the form of a truncated cone, and two copper



FIGS. 406, 407.—Location of 12 in. and 8 in. Protected Bonds for B.S.S. Tramway Rails.

thimbles which are tapered inside to fit on the ends of the rod. In fixing this type of bond, the ends of the rod are placed into freshly-drilled holes in the web of the rail, the thimbles are slipped on from the other side, and the terminals are expanded into the holes by a screw or a hydraulic press. The bond is fixed outside the fish-plates after the latter are in position. The overall length of the bond is 32 in., and two bonds are usually fitted to each rail joint.

The **protected (flexible) bond** (Fig. 405) is designed for fixing to the rail under the fish-plates. It is made from flat copper wire, with forged copper terminals. A bond having a cross-section equivalent to 4/0 B. & S. gauge (0.166 sq. in.) consists of twenty-four strands of flat copper wire (0.193 in. \times 0.036 in.), with terminals $\frac{7}{8}$ in. in diameter by $\frac{3}{4}$ in. long, and shoulders $\frac{1}{4}$ in. thick. The shoulder at the terminal is the thickest part of the bond, so that there is plenty of room for this bond between the web and fish-plate. Two sizes are used in connection with standard tram rails, one (12 in. long) suitable for rail sections Nos. 1 to 3, where only one bond can be placed on the same side of the web (Fig. 406), and the other (8 in. long) suitable for rail sections

Nos. 4 and 5, where two bonds may be placed on the same side of the web (Fig. 407). The terminals of the bonds are expanded into the rail, under a pressure of 20 to 30 tons, by a screw or hydraulic press.

The **screw press** is shown in Fig. 408. The outer (square-threaded) screw, carrying the handwheel and hexagonal nut, is used for clamping the press to the rail, the head of the press bearing against the shoulder of the bond, and the end of the screw against the web. The inner screw is used for expanding the bond terminal, and the end in contact with the bond is pointed. When this screw is tightened, the bond terminal is expanded into the rail, and a button-head is formed on the terminal on the opposite side to the shoulder.

Where welded rail-joints are adopted, it is general practice to fix one bond over the joint in order to obtain increased conductivity.

In addition to bonds between the rail-joints, the rails are **cross-bonded** at intervals of 40 yds., and on double track cross-bonds are

FIG. 408.—Method of Fixing Protected Bonds with Screw Press.

fitted between the tracks at intervals of 80 to 100 yds. At junctions and special work the rails should be bonded independently of the points and crossings.

The **contact resistance** of a bond terminal in a rail is largely influenced by the state of the hole and the terminal at the time of bonding. In order to obtain the minimum contact resistance, it is necessary that the hole and the bond terminal be both clean, dry, and bright. Tests have shown that the contact resistance of a $\frac{7}{8}$ -in. terminal, in a rail with a web $\frac{1}{2}$ in. thick, may be as low as two microhms when the hole and bond are very clean. A thin film of oil or oxide on the bond or hole is sufficient to increase this resistance two to three times the original value.

It is general practice to bond rails weighing 100 lb. per yard and above with two 4/0 (B. & S. gauge) bonds per joint, and, when these bonds are placed outside the fish-plates, the resistance of the joint would be about 65 microhms,* neglecting the conductivity of the fish-plates.

* Obtained as follows: Length of each bond, 30 in.; area of cross-section (4/0 B. & S.), 0.166 sq. in.; resistance (20° C.), 123 microhms; total contact-resistance per bond (say), 7 microhms; total resistance per bond, 130 microhms. Resistance of two bonds in parallel, 65 microhms.

The latter, however, contribute to the conductivity of the joint, but the contact resistance at the fishing surfaces is variable and cannot be depended upon. With fish-plates properly fitted the resistance of the joint without bonds may be 20 microhms (or less), but this will be considerably increased when any looseness occurs between the fish-plates and the rails. Taking the value of 20 microhms for the resistance of the fish-plate portion of the joint, the total resistance of the above bonded joint (for rails weighing 105 lb. per yard) will be about 17 microhms, which is equivalent to 26 in. of the rail. With protected type 8 in. bonds under the fish-plates, the resistance of the joint will be about 12 microhms, which is equivalent to 15 in. of the rail. If, however, the contact resistance of the fish-plates increases, the advantage of the short bonds will be much greater.

CHAPTER XXIII

CONDUCTOR RAILS AND TRACK-WORK FOR ELECTRIC RAILWAYS

On electric railways the track rails in many cases are used as the return conductor.

The **bull-head** type of rail is used for the track by all the large railways in this country, while the Vignoles or flat-bottomed rail is generally used in America. Particulars of standard sections of bull-head rails are given in Table XXIV.

TABLE XXIV
DATA OF STANDARD BULL-HEAD RAILWAY RAILS

B.S. section (indicating the weight in lb. per yard)	60	65	70	75	80	85	90	95	100
Height of rail (in.)	4½	4¾	5	5½	5¾	5¾	5¾	5¾	5¾
Width of head (in.)	2⅞	2¾	2⅞	2½	2⅞	2½	2½	2½	2½
Thickness of web (in.)	1½	1½	1⅞	1⅞	1⅞	1½	1½	1½	1½
Cross-sectional area (sq. in.)	5·87	6·34	6·88	7·32	7·8	8·33	8·81	9·28	9·8
Perimeter (in.)	16·04	16·87	17·85	18·34	18·76	18·93	19·01	19·06	19·11

The **chemical composition** recommended by the Engineering Standards Committee is :

Carbon	0·35 to 0·5 per cent.
Manganese	0·7 to 1·0 per cent.
Silicon not greater than	0·1 per cent.
Phosphorus not greater than	0·075 per cent.
Sulphur not greater than	0·08 per cent.
Iron	98·695 to 98·245 per cent.

Several railways, however, have their own special composition for rails, and in many cases rails made by the Sandberg process are in use.

Where the track rails are used as the return conductor, the voltage drop in the rails is limited to seven volts on systems operating with continuous current, and to about fifteen volts on systems operating with alternating current (since electrolytic effects are much smaller with alternating current than with continuous current). The track-rail joints are bonded in a manner similar to those on tramways, and cross-bonds are fixed between the rails, and also between the tracks, at frequent intervals. On alternating-current railways the rails are also bonded to the structures supporting the overhead conductors.

The ohmic resistance of steel rails to alternating current is much higher than the resistance to continuous current, due to the non-uniform distribution of current through the cross-section in the former case. On account of the magnetic properties of the rail, the alternating current is practically confined to a thin surface layer of a few millimetres. In addition to this increase of resistance, the magnetic properties of the rail considerably increase the inductance. If alternating-current traction were adopted on a large scale, it might be desirable to use a rail of poor magnetic quality, *e.g.* one containing a fairly high percentage of manganese. The increased cost of such a rail would have to be balanced against the decreased cost of feeders and the wearing qualities. The inductance and resistance of rails, and their influence on the design of feeders for alternating-current railways are treated in Chapter XXVI.

On continuous-current railways the current is usually supplied to the trains through one or two **conductor rails**, the latter number being adopted when the track rails are not used as the return conductor. The wear on conductor rails is only that due to the friction of the collector shoes, and, as the strength of the rail is unimportant, the design, as far as the cost will permit, can be made from an electrical standpoint. The principal considerations, other than conductivity and cost, are : (1) the contact surface available for the collector shoes ; (2) the shape of the section (with reference to installation and insulators) ; (3) the wearing qualities.

Steel is adopted for reasons of economy, and the composition is arranged so that the highest conductivity is obtained consistent with the above conditions. The **influence of the chemical composition of iron and steel on the electrical resistance** is shown in Table XXV.*

TABLE XXV
VARIATION OF RESISTANCE OF IRON AND STEEL WITH CHEMICAL COMPOSITION (J. A. CAPP)

Impurities.					Resist- ance relative to Copper.	Tempera- ture.	Remarks.
Carbon.	Man- ganese.	Phos- phorus.	Silicon.	Sulphur.			
per cent.	per cent.	per cent.	per cent.	per cent.		Deg. C.	
0.33	1.27	0.09	0.05	0.05	13.2	19	} Track rails.
0.17	1.09	0.09	0.004	0.054	12.12	20	
0.22	1.08	0.1	0.05	0.05	11.51	20	
0.36	0.87	0.08	0.04	0.09	10.04	19	
0.144	0.46	0.09	Trace.	0.08	8.42	23.5	} Conductor rails.
0.05	0.19	0.054	0.03	0.059	6.4	19	
0.16	0.074	0.12	0.1	0.027	7.41	26	Refined bar iron.
0.08	Nil.	0.13	0.024	0.008	7.11	25.5	} Special refined bar iron.
0.17	0.027	0.074	0.077	0.022	6.76	25.5	
0.06	0.1	0.014	0.012	Trace.	6.17	24	Swedish iron.

* *Transactions of American Institute of Mining Engineers*, vol. 34, p. 400. Paper by J. A. Capp on "Tests of Steel for Electrical Conductivity." See also the investigations of Barrett, Brown, and Hadfield in the *Transactions of the Royal Society of Dublin*, vol. 7, Series 2, Part 4.

Of the impurities usually found in steel, carbon and manganese have the greatest effect on the resistance. Considering pure iron, the addition of carbon increases the resistance fairly rapidly until 0.3 per cent. of carbon is reached, after which the increase of resistance is practically proportional to the increase of carbon. Manganese has a much greater effect on the resistance than carbon, until about 10 per cent. of manganese is reached, after which the addition of manganese has very little effect.

In practice the steel used for conductor rails has a specific resistance of about seven times that of copper. Table XXVI gives data of the composition and resistance of conductor rails on various railways.

Classification of Conductor Rails.—The conductor rails in general use may be divided into three classes according to the position of the

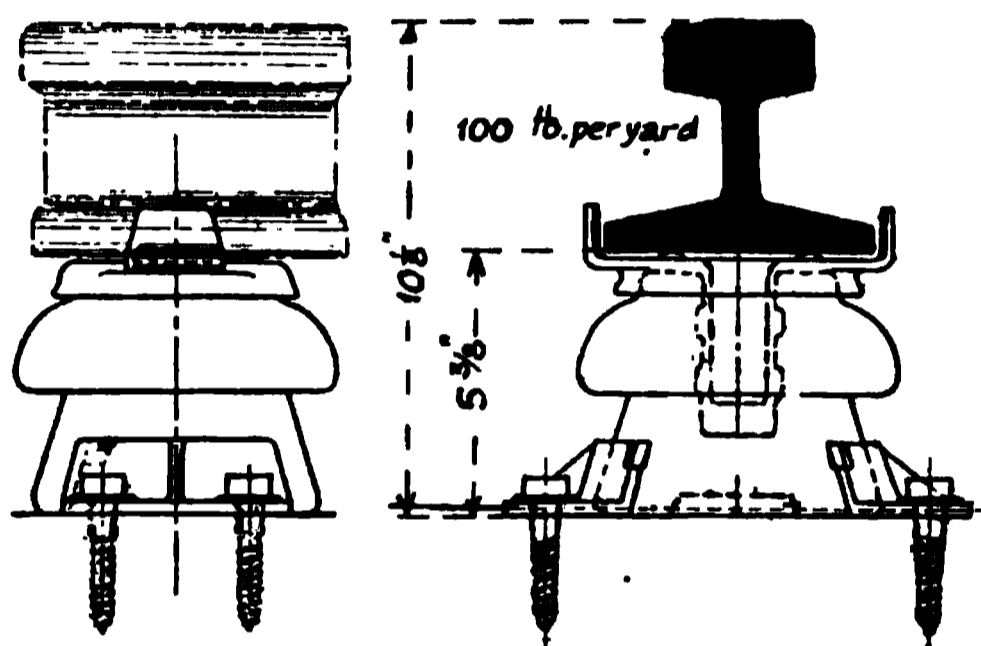


FIG. 409.—Method of Mounting "Vignoles" Type Conductor Rails.

contact surface. For instance, the contact surface may be either at the top, bottom, or side of the rail. Hence the classification of the rails becomes: (1) top-contact rails, (2) under-contact rails, (3) side-contact rails.

The top-contact rail is used universally for low-voltage (600 volts) electrifications in this country, while the side-contact rail has recently been developed for the 1200-volt electrification

of the Manchester-Bury section of the Lancashire and Yorkshire Railway. The under-contact rail has been developed by the General Electric Company (U.S.A.) for high- and low-voltage lines.

The **type of section** adopted for top-contact conductor rails is usually the Vignoles or flat-bottomed section, although channel and special rectangular sections have been used in some installations. The conductor rails for the early electric railways were of channel section, and were very light in weight, the original conductor rail (installed in 1890) on the City and South London (tube) Railway weighing only 10 lb. per yard. The conditions of modern traffic, however, require a much heavier rail, and sections weighing 100 lb. per yard are generally used for urban and suburban railways.

For under-contact conductor rails a bull-head section is usually adopted, although a special channel section (described below) has been developed for high-voltage work.

For side-contact conductor rails a special angle section is adopted.

Drawings of typical sections showing the insulators and the methods of mounting are given in Figs. 409–415. Fig. 409 shows the type of rail and insulator which has been standardised for low-voltage electrification in this country. The rail (which usually weighs 100 lb. per yard) rests on a malleable-iron cap which is fixed to the top of a petticoated "pedestal type" porcelain insulator, the latter being illus-

TABLE XXVI

CHEMICAL COMPOSITION AND RESISTANCE OF CONDUCTOR RAILS ON BRITISH RAILWAYS

Railway.	Impurities.					Resistivity.	
	Carbon.	Man-ganese.	Phos-phorus.	Silicon.	Sulphur.	Ratio of Specific Resistance of Rail to Specific Resistance of Copper at 20° C.	Specific Resistance.
North-Eastern	per cent. 0·05	per cent. 0·4	per cent. 0·1	per cent. 0·2	per cent. 0·08	7·25	microhms per inch cube. 4·93
Lancashire and Yorkshire (600-volt lines)	0·045	0·23	0·046	Trace	0·04	7·23	4·91
Lancashire and Yorkshire (1200-volt lines)	0·08	0·22	0·034	0·022	0·026	6·75	4·6
Metropolitan District (London)	0·035	0·315	0·056	Nil	0·059	6·5	4·42
London and North-Western *	0·044	0·139	0·011	0·03	0·029	6·5	4·42
London and South-Western	0·047	0·34	0·053	Trace	0·055	6·75	4·6
Central London	{ 0·03 0·05	0·33 0·19	0·052 0·05	Trace 0·03	0·045 0·05	7·5† 6·4‡	5·1 4·35
London Electric (tube) Railways	0·05	0·19	0·05	0·03	0·05	6·4	4·35

* This conductor rail contains 0·255 per cent. nickel.

† Original conductor rail.

‡ Conductor rail used for extensions and renewals.

trated in detail in Figs. 410, 421. The base of the insulator rests directly upon one of the sleepers carrying the track rails, and is secured in position by two malleable-iron clamps. The insulator is a considerable improvement over the earlier types with metal bases, as the whole distance between the sleeper and the conductor rail is utilised for insulation, thereby obtaining a maximum length of leakage path. The wide petticoat is also advantageous in keeping the lower part of the insulator dry.

Fig. 411 shows the type of conductor rail and tubular insulator in use on the tube railways of the London Electric Railways. The difference in the shape of the insulators for the positive and negative

FIG. 410.—Doulton's "Pedestal" Insulator for "Vignoles" Type Conductor Rails.

conductor rails is due to the short length of the sleepers. The location of the insulators and conductor rails with respect to the track rails can be seen in Figs. 417, 420.

The method (developed by the General Electric Company) of supporting and insulating conductor rails of the under-contact type is shown in Fig. 412. The conductor rail is supported from cast-iron brackets (fixed to the sleepers) by means of special porcelain insulators, which are in halves and are held in position by a hook bolt. The portion of the rail between the insulators is protected by either wooden or fibre protection, so that only the lower (or contact) surface of the rail is exposed. One advantage of this type of rail is that the contact surface is protected from snow, sleet, and ice. This type of rail is in use on the New York Central, Pennsylvania, and other railways in America.

Conductor Rails for High-voltage Circuits.—When conductor rails are to be used on high-voltage circuits, the insulation and pro-

tection of the rail must be given special consideration. As far as protection is concerned, the under-contact and side-contact types possess advantages over the top-contact type, and although the latter type of rail is in service for 2400 volts,* the former types are usually adopted for 1200, 1500, or 2400 volts.

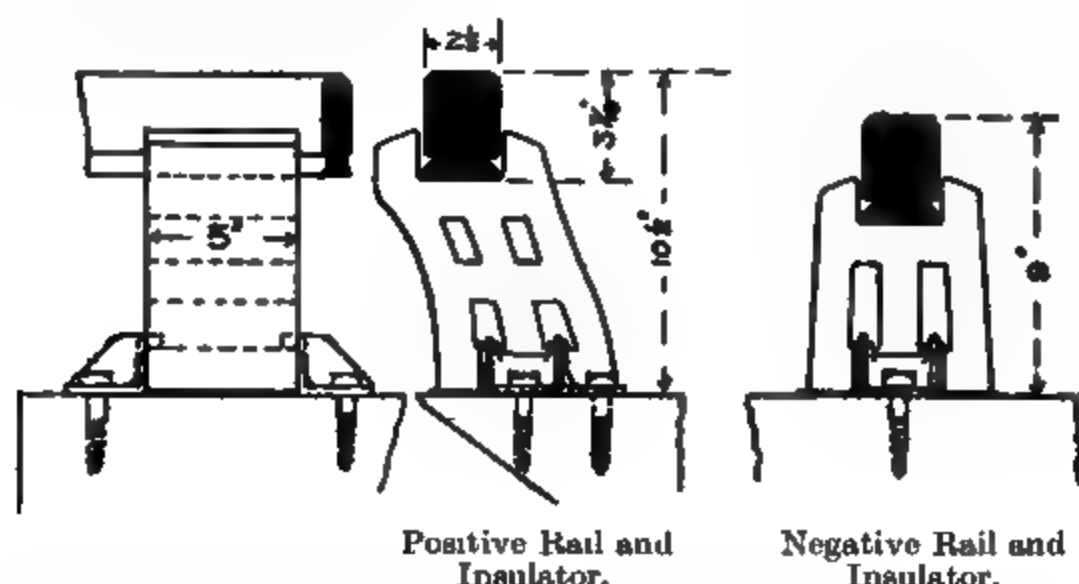


FIG. 411.—Method of Mounting "Solid" Type Conductor Rails.

The **under-contact rail**, illustrated in Fig. 413, has recently been developed by the General Electric Company for 2400 volts. The general features of the low-voltage type (shown in Fig. 412) have been retained, but the insulation and protection have been modified. The conductor rail (of bull-head section) is held in special clips which are fixed

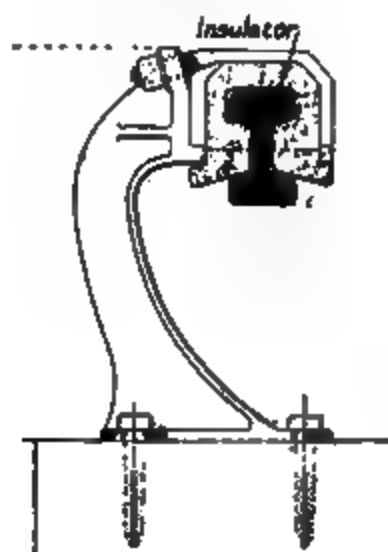


FIG. 412.—Method of Mounting Under-contact Conductor Rails.

between two insulators in the manner shown in Fig. 413. The protection consists of an inverted trough of wood, which is maintained in position on the conductor rail by means of porcelain distance pieces.

Another type of under-contact conductor rail is shown in Fig. 414. This type of rail has been designed by Messrs. Merz & Redman for 1500-volt railways, and has the special feature that double insulation is adopted.

* On the Michigan Central Railroad. See *Electric Railway Journal*, vol. 44, p. 376.

The conductor rail *D* is of special channel section, and is supported on auxiliary insulators *C*, which are placed on the upper part of the bracket *B*. This bracket is fixed to the main insulator *A*, which is of the pedestal type (Fig. 410), and is fixed to the sleeper in the usual manner. The protection *E* is of stoneware or fibre. An important feature of the design is that the rail is suitable for systems on which the clearances

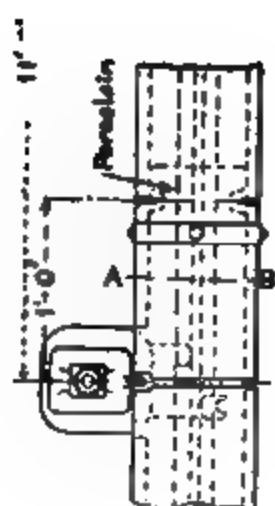
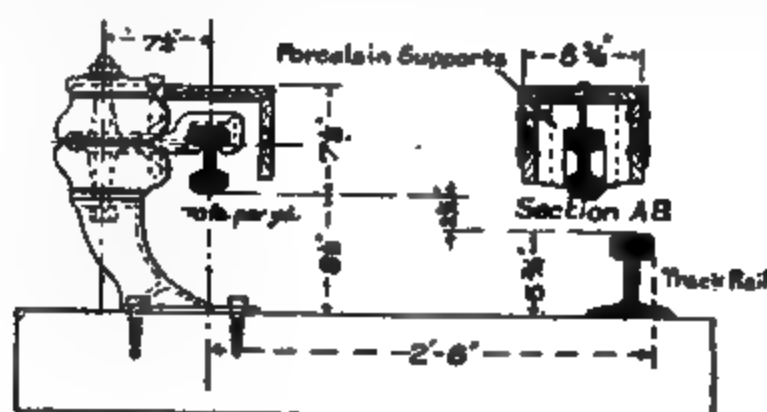


FIG. 413.—General Electric Under-contact Conductor Rail for 2400 Volts.

between structure and loading gauges are restricted, these conditions preventing the use of the G.-E. under-contact rail (Fig. 413).

The **side-contact type** of conductor rail is due to Mr. J. A. F. Aspinall, and is installed on the Manchester-Bury (1200-volt) section of the Lancashire and Yorkshire Railway. A drawing of the rail, showing the protection and method of mounting, is given in Fig. 415,* while

* The author is indebted to Mr. J. A. F. Aspinall (General Manager of the Lancashire and Yorkshire Railway) for the illustrations and details of the side-contact conductor rail.

a view of the track equipped with this type of rail is shown in Fig. 416.*

Referring to Fig. 415, the conductor rail *C* (which weighs 85 lb. per yard) rests upon a block of wood *B* located in a recess formed in

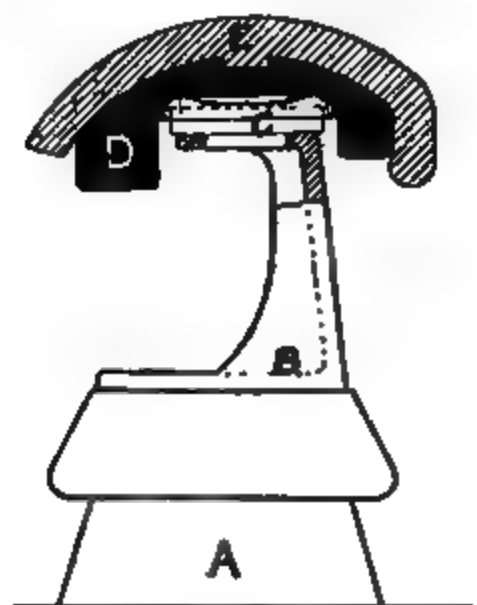


FIG. 414.—Merz-Redman Under-contact Conductor Rail for 1500 Volts.

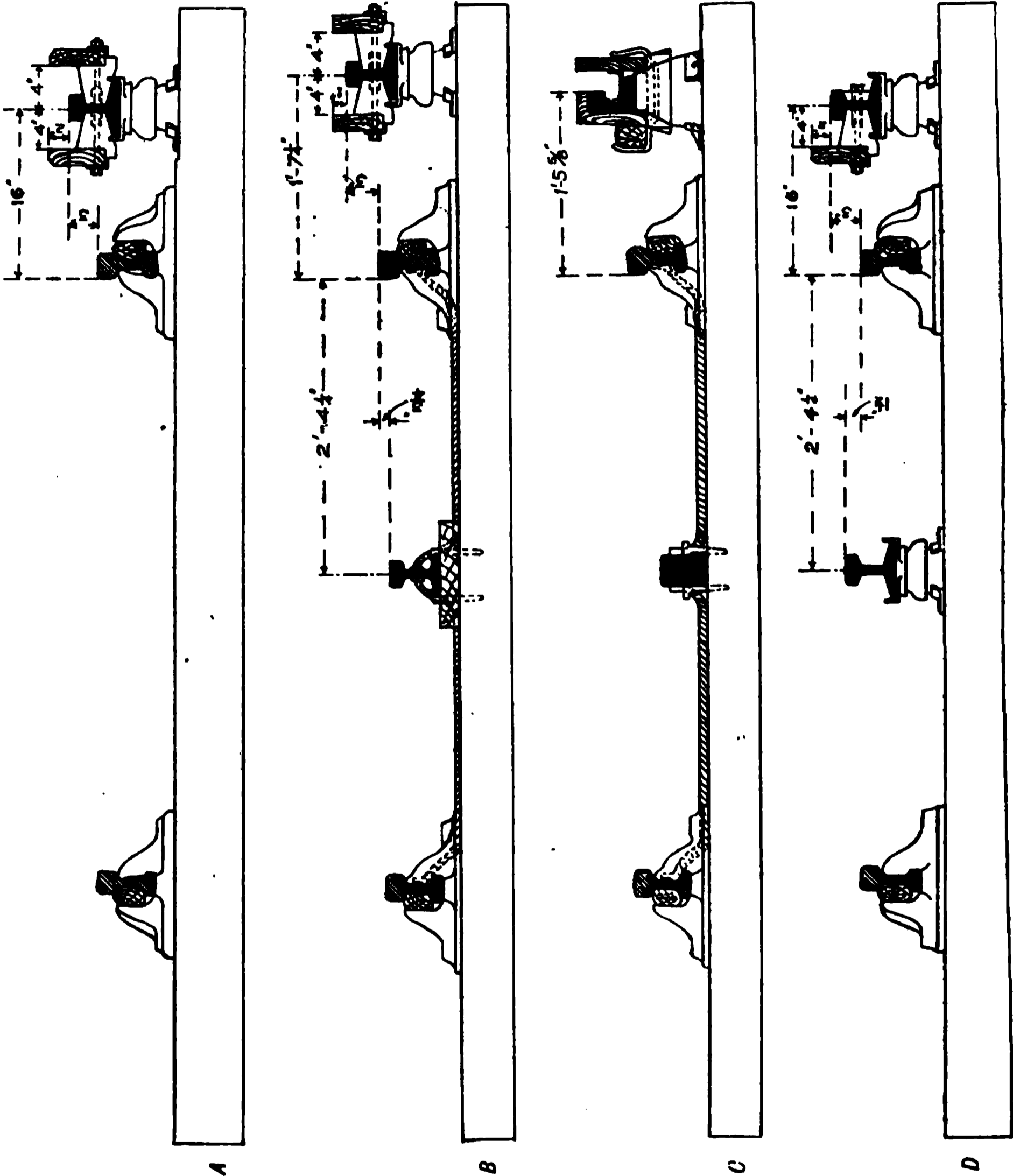
FIG. 415.—Aspinall Side-contact Conductor Rail for 1200 Volts.

the top of the porcelain insulator *A*. The latter is of the pedestal type, and is fixed to the sleeper in the usual manner. The two wooden protecting guards, *E*, *F*, project 1 in. below the flange of the conductor rail,

FIG. 416.—Double Track equipped with Aspinall Side-contact, 1200-volt, Conductor Rails (Lancashire and Yorkshire Railway).

and thus prevent the possibility of the permanent-way staff coming into contact with the underside of the rail. This projection of the guards below the flange of conductor rail also prevents transverse movements of the latter.

* See Fig. 239 (p. 284) for views of the collector shoe.



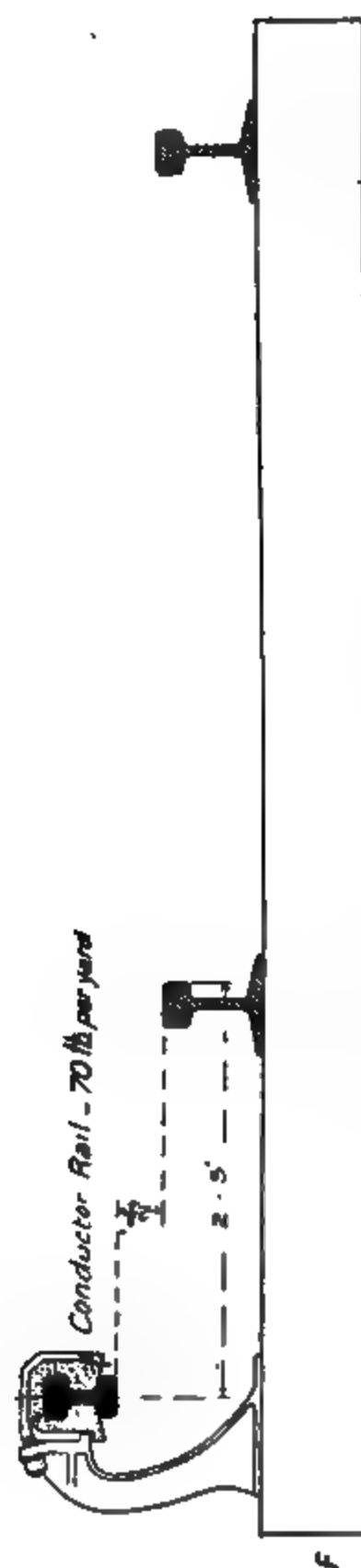


FIG. 417.—Cross-sections
 Western Ry.; B, L
 Ry. (1200-volt lines); U, Metropolitan and District Rys., and London and North-Western Ry.;
 E, London Electric (tube) Rys.; F, New York Central Ry.

Attention must be directed to the shape of the inner protecting guard *F*. This guard is sawn out of the solid in order to avoid the possibility of any nails or screws coming into contact with the conductor rail.

The protecting guards rest upon ledges formed on the insulator, while the guards and the conductor rail are maintained in their correct positions by means of distance pieces *D*, spring clips *G*, and keys *H* (which are standard permanent-way keys). The distance pieces *D* are placed at intervals where it is found that they are necessary. In this manner a space $\frac{1}{2}$ in. wide is obtained between the flange of the conductor rail and the outer protecting guard, so that no accumulation of water can occur inside the guards.

The positions of the conductor rails with respect to the track rails will depend on the type of conductor rail and the rolling-stock gauge. In this country the following standard positions have been adopted for top-contact conductor rails :—

(a) When the conductor rail is located between the track rails: centre-line of conductor rail to coincide with the centre-line of the track rails, and the top of conductor rail to be $1\frac{1}{2}$ in. above the top of track rails.

(b) When the conductor rail is located outside the track rails: centre-line of conductor rail to be 1 ft. $7\frac{1}{4}$ in.* from gauge line of nearest track rail, and the top of conductor rail to be 3 in. above the top of track rails.

Cross-sections of single track for typical electric railways are given in Fig. 417. In these diagrams the protection of the rail at stations is also shown, this protection (for top-contact rails) being in the form of wooden boards fixed on each side of the conductor rail.

Diagram *A* refers to the London and South-Western Railway, on which the track rails are used as the return conductor.

Diagram *B* refers to the 600-volt (Liverpool-Southport) system of the Lancashire and Yorkshire Railway, on which the track rails and an uninsulated conductor rail (located between the track rails) are used as the return conductor. The joints in both conductor rails are bonded, and the track rails are cross-bonded to the uninsulated conductor rail at each joint.

Diagram *C* refers to the 1200-volt (Manchester-Bury) system of the Lancashire and Yorkshire Railway. In this case the uninsulated return rail is of square cross-section in order to reduce the area exposed to the atmosphere, and therefore minimise corrosion.†

Diagram *D* refers to the Metropolitan and District (London) Railways, and the London suburban system of the London and North-Western Railway, on which systems insulated positive and negative conductor rails are adopted.

Diagram *E* refers to the track construction on the London Electric (tube) Railways.

Diagram *F* is typical of the track construction adopted for the under-contact conductor rail.

The Bonding of the Conductor Rails.—As the conductor rails are used solely as electrical conductors, and on a large system may have

* This dimension is 16 in. for the London Railways.

† The corrosion of conductor rails is considerably greater than that of track rails. See Mr. Aspinall's Presidential Address, *Proceedings of the Institution of Mechanical Engineers* (1909), p. 436.

to carry currents of 2000 amperes for short periods, it is necessary to bond the joints to the full current-carrying capacity of the rail. The bonds are similar in type to those used on tramways, but are flexible, shorter, and of larger cross-section. With the Vignoles type of conductor rail the bonds are usually fixed to the foot or flange, while for the solid type (Fig. 411) they are located at the sides of the rail.

A typical bond (for the Vignoles type of rail) is shown in Fig. 418, and a drawing showing a bonding for a 100lb. conductor rail is given in Fig. 419.

Table XXVII gives particulars of the bonding of conductor rails for the railways in this country.

Feeder cables (and jumper cables) may be connected to the conductor rails by means of either several bonds with cable sockets, or a special copper plate (which is provided with cable sockets) bolted to the web of the rail. An example of the latter method is shown at A in Fig. 420.

At **cross-overs and special track-work** it is necessary to insert gaps in the conductor rails. The continuity of the various conductor rails of similar polarity is maintained by jumper cables.

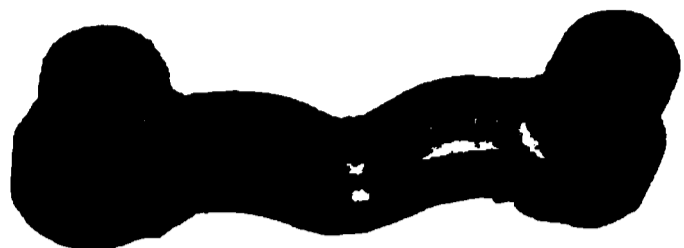


FIG. 418.—Flexible Bond for Conductor Rails.

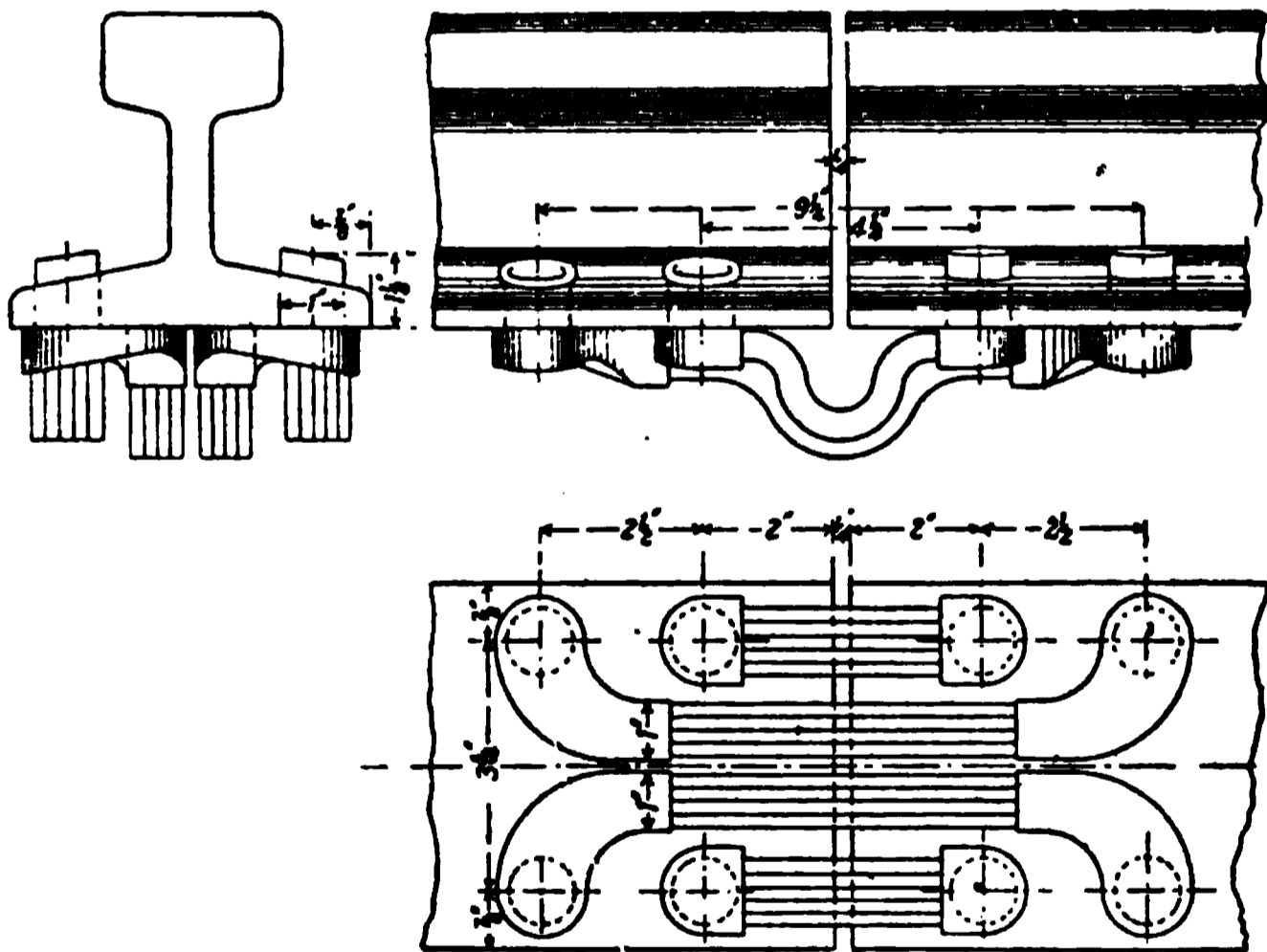


FIG. 419.—Bonding for 100-lb. Conductor Rails. NOTE.—Each bond has a cross-section of 0.35 sq. in.

In Fig. 420 is shown a view of the conductor rails at a cross-over road. It will be observed that the ends of the conductor rails are formed into ramps, by means of which the collector shoes are prevented from fouling when a train is passing over the special track-work.

In order that the supply of current to the train shall not be interrupted when it is passing over special track-work, the distance apart of the front and rear collector shoes must be greater than the longest

gap in the conductor rails. In some cases (for example, in locomotives, single motor-coaches, and motor-coach trains for tube railways, where no "bus lines" are allowed on the train) it will not be possible to fulfil

FIG. 420.—Cross-over on London Tube Railway, showing Location of Positive and Negative Conductor Rails. At A is shown a cable terminal plate. NOTE.—The train consists of three coaches—one motor-coach (at rear) and two trailer coaches. The vestibule of the leading (trailer) coach is arranged for driving, and is provided with a master controller, brake valve, and control-circuit switches.

this requirement, and under these circumstances the train will have to coast over the gap.

At large freight yards it will not be possible to instal conductor

rails, as, in addition to the complication to the track and the danger to the shunters, the lengths of the gaps would be too great to be bridged by the collector shoes on a locomotive, and in shunting operations it is essential that the locomotive should be able to obtain current at any position. Overhead work must therefore be erected at these places, and the locomotive must be equipped with a bow collector, as shown in Fig. 307, p. 375.

The conductor rails are divided into **sections** of convenient length,

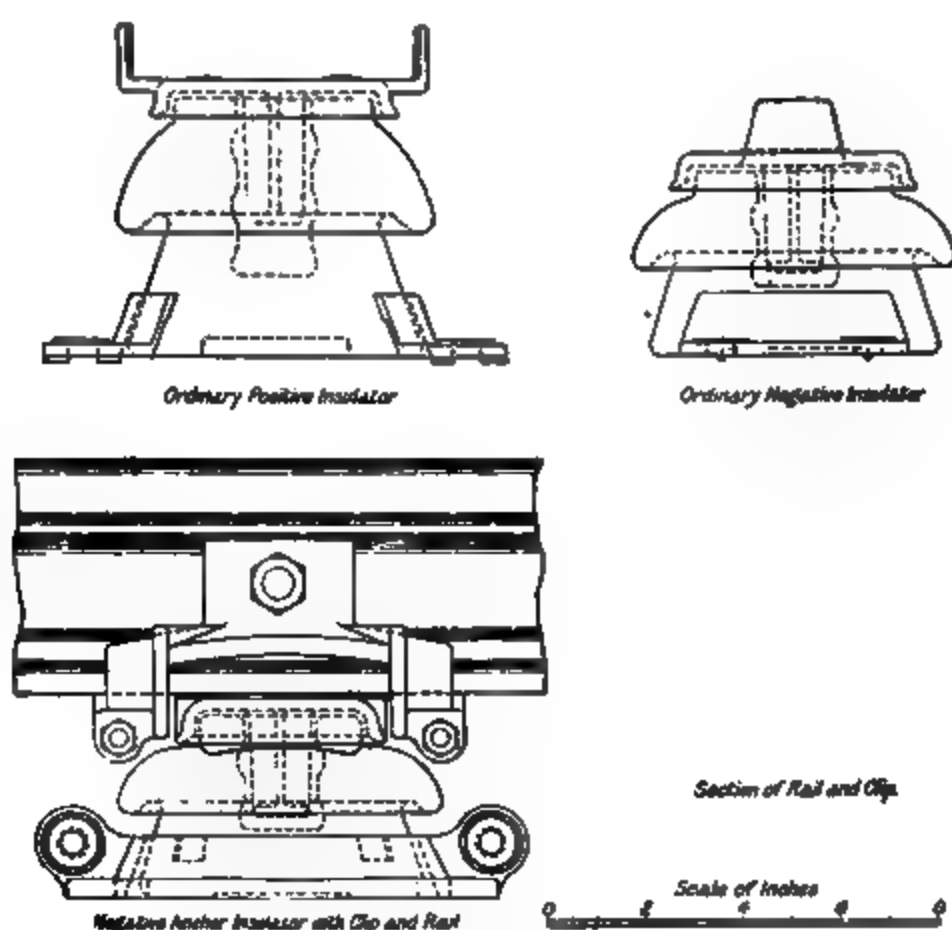


FIG. 421.—Detail of Doulton's Conductor Rail Insulators, and Method of Anchoring Conductor Rail (London and North-Western Railway).

and the section insulators are usually arranged near the sub-stations. [The feeding and switching arrangements for the conductor rails and section insulators are discussed in Chapter XXVI.] Each section is anchored at one point, either by bolting to the rail a special anchor clip and anchoring one of the insulators, as shown in Fig. 421,* or by means of insulated anchor ties.

* Messrs. Doulton & Co. (to whom the author is indebted for Figs. 410, 421) have informed the author that the type of anchor insulator illustrated in Fig. 421, and the method of anchoring to the sleeper, are covered by their patent, but the special rail clips used in conjunction with the anchor insulators are covered by the patent of Mr. H. Scott, of the London and North-Western Railway. The method of anchoring has also been adopted on the London and South-Western Railway.

TABLE XXVII
DATA OF CONDUCTOR RAILS AND BONDING (BRITISH RAILWAYS)

Railway	Type of Section.	Conductor Rails.				Bonding.		
		Weight.	Cross-sectional Area.	Height.	Dimensions.	Number of Bonds per Joint.	Size of Terminals.	Total Cross-section of Bonds per Joint.
					Width of Base.	Width of Head at Contact Surface.		
		lb. per yard.	sq. in.	in.	in.	in.	sq. in.	sq. in.
North Eastern	Vignoles.	80	7.83	5½	5½	2½	0.166	0.66
Lancashire and Yorkshire (600-volt lines)	..	70	6.86	4½	4½	2½	0.166	0.66
Lancashire and Yorkshire (1200-volt lines)	{ Special angle. (See Fig. 415.) }	85	8.5	4⅝	3½	1½	0.4	0.8
Metropolitan District (London)	Vignoles.	100	9.8	4¾	5½	2¾	0.35	1.4
London and North-Western	..	105	10.4	4¾	5½	2¾	0.35	1.4
London and South-Western	..	100	9.8	4¾	5½	2¾	0.35	1.4
Central London	{ Channel. Special solid.	85 85	8.37 8.37	2¾ 3¼	2½	4½ 2½	0.155 0.33	0.62 1.33
London Electric (tube) Railways	{ Special solid. (See Fig. 411.) }	85	8.37	3⅞	2½	2½	0.33	1.33
Great Western (London)	Special channel.	102.8	10	4½	..	3½	0.31	1.24

CHAPTER XXIV

OVERHEAD CONSTRUCTION FOR TRAMWAYS

THE overhead trolley system for tramways is very extensively used in this country and America. At the present time (1916) it is estimated that there are approximately 2500 route miles of overhead construction in Great Britain.

Overhead construction has been standardised for a number of years, and modern installations show only improvements in a few details. The Board of Trade require the overhead conductor or trolley-wire to be erected at a minimum height of 17 feet above the street surface (except under bridges), and to be supported at intervals not greater than 120 feet. Further, each trolley-wire must be divided into sections, not exceeding one-half of a mile in length, with an emergency switch between every two sections.

In addition to satisfying the Board of Trade requirements, the trolley-wire must be designed to fulfil its function as an electrical conductor and to withstand the mechanical stresses due to temperature variation, &c. The material in general used is hard-drawn copper, although various silicio-bronze alloys (which have better wearing qualities than copper) have been used to a limited extent. The mechanical and electrical properties of hard-drawn copper trolley-wire and an alloyed trolley-wire are given in Tables XXVIII, XXIX, from which it will be observed that the alloyed wire has a tensile strength approximately 35 per cent. greater than that of copper. The resistance of the alloyed wire, however, is 133 per cent. greater than that of copper, so that the use of the former would require a greater cross-section in the feeders. It has been suggested * that, for heavy traffic, a small size (No. 0 S.W.G.) of alloyed wire should be used for the trolley-wire, and that a bare copper wire be connected in parallel with it to reduce the resistance. One reason for adopting this arrangement, instead of using copper trolley-wires of large size, is that the wearing qualities of hard-drawn copper wire are not directly proportional to its weight, on account of the hardness being confined to the outer skin. The small alloyed wires, being uniformly hard throughout, have better wearing qualities than large copper wires, and also have sufficient mechanical strength for tramway purposes.

* Paper on "Suggested Economics in Tramway Working," by R. G. and J. G. Cunliffe (Municipal Tramways Association, Annual Convention, September 1908). See *The Electrician*, vol. 61, p. 1003.

TABLE XXVIII

PROPERTIES AND DATA OF HARD-DRAWN COPPER TROLLEY-WIRE

Ultimate tensile strength	. . .	23–25 tons per sq. in.
Elastic limit	. . .	7.5–12.5 tons per sq. in.
Young's modulus of elasticity	. . .	18×10^6 lb. per sq. in.
Specific resistance (60° F.)	. . .	0.69×10^{-6} ohm per in. cube.

Gauge.	Diameter.	Cross-section.	Breaking Load.	Elastic Limit.	Weight.		Resistance (60° F.).	
					Per 1000 Ft.	Per Mile.	Per 1000 Ft.	Per Mile.
S. W. G.	in.	sq. in.	lb.	lb.	lb.	lb.	ohms.	ohms.
5/0	0.432	0.147	7570	2470	566	2990	0.0564	0.297
4/0	0.4	0.1257	6500	2120	484	2560	0.066	0.347
3/0	0.372	0.1087	5600	1840	419	2212	0.0756	0.4
2/0	0.348	0.095	4900	1600	367	1935	0.087	0.46
1/0	0.324	0.082	4220	1380	317	1670	0.11	0.533

TABLE XXIX

PROPERTIES AND DATA OF ALLOYED “PHONO-ELECTRIC”
TROLLEY-WIRE

Ultimate tensile strength	. . .	31–35 tons per sq. in.
Elastic limit	. . .	24–25 tons per sq. in.
Specific resistance (60° F.)	. . .	1.61×10^{-6} ohm per in. cube.

Gauge.	Diameter.	Cross-section.	Breaking Load.	Elastic Limit.	Weight.		Resistance (60° F.).	
					Per 1000 Ft.	Per Mile.	Per 1000 Ft.	Per Mile.
B. & S.	in.	sq. in.	lb.	lb.	lb.	lb.	ohms.	ohms.
4/0	0.46	0.166	11460	9200	640	3382	0.116	0.612
3/0	0.4096	0.132	9140	7340	508	2682	0.147	0.776
2/0	0.365	0.104	7400	5840	403	2127	0.1865	0.985
1/0	0.325	0.083	6300	4550	319	1687	0.234	1.235

Trolley-wire can be obtained with circular and grooved cross-sections, the latter being used to a large extent in modern installations. The advantages of grooved wire are:—

- (1) The suspension fittings, or ears (Fig. 422), can be clipped to the wire, whereas with circular wire these fittings must be soldered, and consequently the physical properties of the wire may be affected by this process.
- (2) The wire can be erected quickly.
- (3) The mechanical fittings (for ordinary grooved wire) can be designed to offer practically no obstruction to the trolley wheel, so that smooth running and freedom from bumping and sparking are obtained,

thereby resulting in low maintenance costs. On the other hand, soldered fittings introduce some obstruction to the running of the trolley wheel, since the arc of contact between fitting and wire is usually greater than 180 degrees (see Fig. 424).

The latest development in grooved wire is illustrated in Fig. 421a, in which is shown a cross-section of the "channel" trolley wire developed by Messrs. The British Insulated and Helsby Cables. This wire possesses all the merits of circular and grooved wires, with the additional important advantage that it admits of the use of mechanical fittings which give exceptionally smooth running to the trolley wheel (see Fig. 422, C, for view of mechanical fitting with length of wire in position).

With reference to the sizes of trolley-wire in use, the *Electrician* tables* show that all the sizes in Table XXVIII have been adopted, the smaller sizes (0 and 2/0) on small systems, and the larger sizes (3/0 and 4/0) on large systems, while the 5/0 size is in use at Manchester for the heaviest traffic.

FIG. 421a.—Prescot "Channel" Trolley-wire (British Insulated and Helsby Cables).

The trolley-wire is supported and insulated from a transverse span-wire by means of an insulated steel bolt screwed into a gun-metal ear attached to the trolley-wire, the bolt being held in a hanger attached to the span-wire.

Various types of ears for circular and grooved wire are illustrated in Fig. 422.

The suspension bolts (Fig. 422a) are of two standard sizes ($\frac{1}{2}$ in. and $\frac{3}{4}$ in.), and are insulated with moulded insulation† (around the head and body) to standard overall dimensions, so that only one size of hanger is required.

The various types of hangers are shown in Fig. 423, while a cross-section of a straight-line hanger, with bolt and ear in position, is shown in Fig. 424.

On curves it is necessary to arrange that the span-wire is attached to the hanger at the same level as the trolley-wire, otherwise the hanger will be pulled out of the vertical. Hangers for curves are called "pull-offs," the double pull-off being used when both sides of the span-wire are in tension.‡

The span-wire is of stranded galvanised or sherardised steel, having properties as given in Table XXX. The wire may extend the whole width of the road (in which case it is attached to poles on each side of the road), or a short length of span-wire carrying the hanger may be attached to brackets carried from poles at the side or the centre of the tracks. These types of construction are known as span-wire, side-pole, and centre-pole. The first two are the more common, as centre-pole construction is only adapted for wide streets or private right-of-way, and its use requires the sanction of the Board of Trade.

* Tables of Electric Tramways and Railways of the United Kingdom.

† Moulded insulation for tramway fittings is usually composed of asbestos, powdered mica, shellac, &c., and is compressed to the required shape at a high temperature.

‡ See Fig. 427 (p. 517) for the use of double and single pull-offs at curves.

TABLE XXX

PROPERTIES AND DATA OF GALVANISED STEEL SPAN-WIRE

Ultimate tensile strength . . . 29 tons per sq. in.
 Elastic limit . . . 20 " "

Gauge.	Diameter of each Strand.	Diameter over all.	Breaking Load.	Elastic Limit.	Weight per 1000 Ft.
S.W.G. 7/10	in. 0.125	in. $\frac{3}{8}$	lb. 4550	lb. 3100	lb. 287
7/12	0.104	$\frac{5}{16}$	3950	2700	186.6
7/14	0.083	$\frac{1}{2}$	2400	1680	123.4

Side-pole construction is generally used with single track, and with double track in narrow streets. The Board of Trade limit the maximum length of the bracket-arm to 16 ft., which allows the trolley-wire to be fixed at a maximum distance of about 14 ft. from the kerb. A swivelling trolley-head (see p. 273) will allow satisfactory operation to be obtained with the trolley-wire 6 ft. from the centre of the track, so that under these conditions the centre of the track can be 20 ft. from the kerb. By working to these extreme limits we could use this construction with double track in streets 32 ft. wide, and with single track in streets 40 ft. wide. It is not always desirable, however, to work to these limits, so that span-wire construction is frequently adopted in streets below 30 ft. in width.

Span-wire construction is suitable for double track in any width of street, and is the only type of construction in use on some of the large tramway systems.

In each type of construction the span-wire is insulated from the poles, and, since the trolley-wire is insulated from the hangers, there is, therefore, double insulation between the trolley-wire and earth.

FIG. 422a.—
Cross-section
of $\frac{1}{2}$ " Insulated Suspension Bolt.

The insulators for the span-wire may consist of moulded material or of porcelain* (the latter being of recent introduction), but in each case the insulation must be arranged so that it is subjected only to compressive stresses. Illustrations of typical insulators are given in Fig. 425, while the mechanical and electrical properties of some of the insulators are given in Table XXXI.

* Porcelain is preferable, in many cases, to moulded insulation for strain insulators. In this connection see a paper on "Overhead Electrolysis and Porcelain Strain Insulators" by S. L. Foster, in which some operating features of porcelain and moulded insulators are given (*Proceedings of the American Institute of Electrical Engineers*, vol. 34, p. 1549).

The advantages and disadvantages of porcelain and moulded strain insulators for tramway purposes are discussed in a paper by Messrs. Tweedy and Dudgeon, on "Overhead Equipment of Tramways" (*Journal of the Institution of Electrical Engineers*, vol. 37, p. 161).

TABLE XXXI

ELECTRICAL AND MECHANICAL PROPERTIES OF STRAIN INSULATORS

Type of Insulator.	Size.	Average Ultimate Mechanical Strength.	Average Breakdown Voltage (Dry).
OB composition (Fig. 425, <i>A</i>)	2½ in. diameter	lb. 7,000	14,000
OB composition (Fig. 425, <i>A</i>)	2¾ in. diameter	9,000	14,000
Porcelain strain (Fig. 425, <i>F</i>)*	3 in. × 1½ in. (⅞ in. holes)	2,000	20,000
Porcelain strain (Fig. 425, <i>F</i>) †	4¾ in. × 2¾ in. (½ in. holes)	10,000	30,000
V.P. link (Fig. 425, <i>G</i>)	2½ in. × 2½ in.	5,200	22,000
V.P. link (Fig. 425, <i>G</i>)	3 in. × 3 in.	6,000	30,000

* Suitable for light pull-off wires. Working load 550 lb.

† Suitable for heavy pull-off, span, and anchor wires. Working load 2500 lb.

The "O.-B." strain insulator (manufactured by the Ohio Brass Co.) is shown at *A* (Fig. 425), and represents the latest development in moulded insulators of the "globe" type. The strain is carried by two malleable-iron castings, one of which is compressed over the other. The insulation between the castings consists of mica, and composition insulation is moulded around the central portion of the castings to protect the mica insulation from the weather and to increase the leakage surface. This composition insulation is securely locked in position by the cup-shaped flanges formed near the eyes of the castings.

The Brooklyn insulator—shown at *B*, Fig. 425—is adjustable, and is insulated with moulded material. This insulator is only used to a limited extent in modern installations.

Porcelain strain insulators, suitable for span-wire construction, are shown at *E*, *F*, *G*, *H*, Fig. 425.*

Examples of overhead construction showing the application of some of these insulators to side-pole and span-wire construction are given in Fig. 426. Diagram *A* shows the use of "globe" strain insulators for side-pole construction, while *B* represents the more modern construction with porcelain insulators, and at *C*, *D*, *E* are shown several alternative methods for span-wire construction, all of which are in use in this country.

At *F* and *G* are shown the two methods of construction which have been adopted on the railless traction systems in this country.

It will be observed from these diagrams that the trolley-wire is flexibly supported from the poles. This feature is essential in all overhead tramway and railway construction, as any rigid parts in the trolley-

* The insulator shown at *H* (Fig. 425) is one unit of the "chain" type of insulator developed by Messrs. Vedovelli Priestley (Paris) for high-voltage lines, and has been adopted as a strain insulator by some of the tramways in this country.

wire will be subjected to hammering from the collector, and will be liable to excessive wear.

At **curved track** the trolley-wire is maintained in position by means of pull-off wires. As the tension in some cases may be considerable,

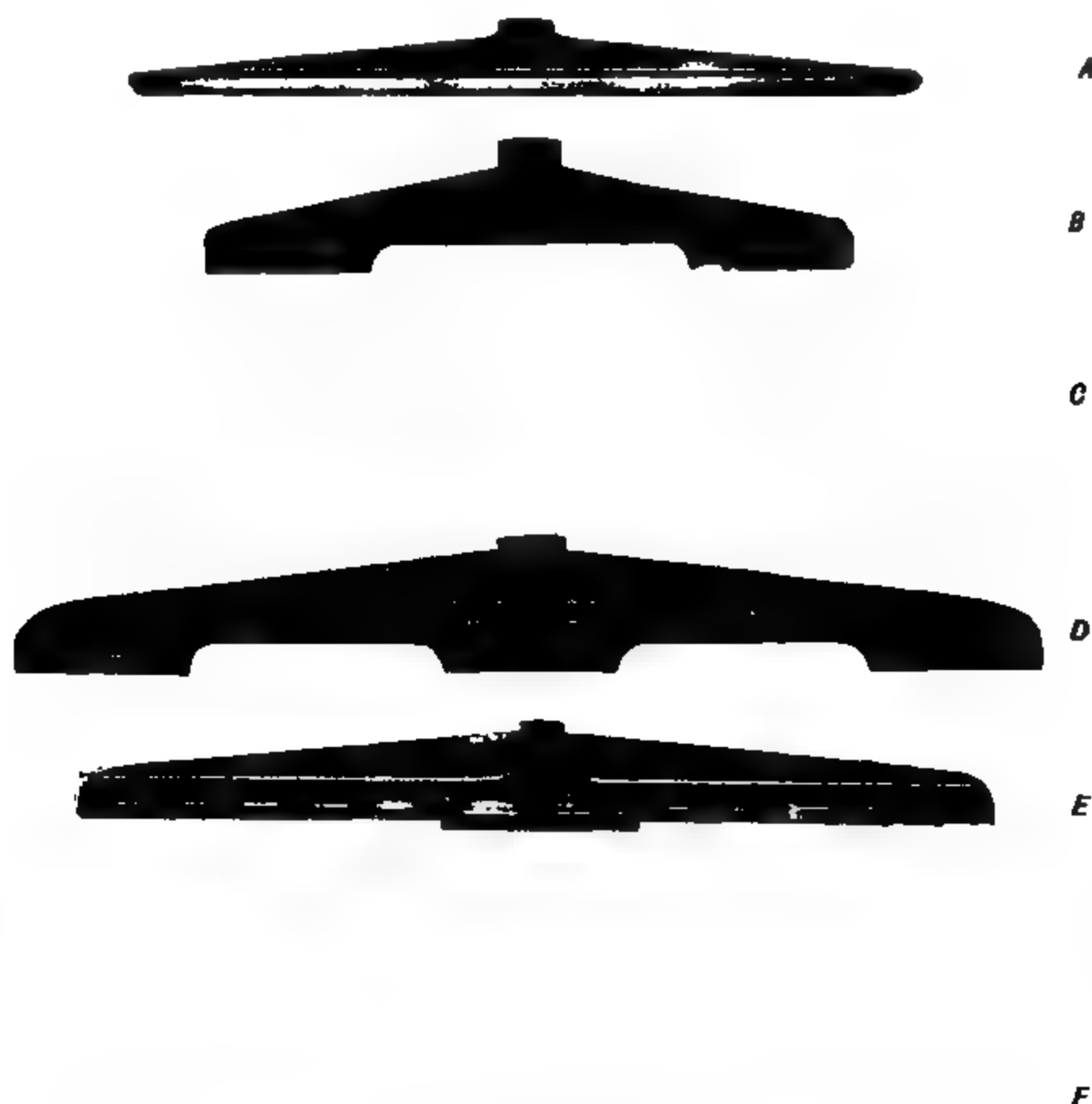


FIG. 422.—Types of Ears for Trolley-wire (British Insulated and Helsby Cables).

- A. Straight-line soldered ear for circular wire.
- B. Straight-line mechanical ear for grooved wire.
- C. Straight-line ear for Prescott channel-grooved wire, with length of wire in position.
- D. Ribbed ear for curves.
- E. Splicing ear.
- F. Combined anchor and feeder ear.

it is usual to employ globe and Brooklyn strain insulators for insulating the pull-off wires from the poles.

The **position of the trolley-wire** relative to the track depends on the type of car, length and elevation of trolley-pole, super-elevation of

track, &c. The ideal position can be obtained from a track plan by using a plan of the car wheel-base and trolley-pole as a template (as indicated in Fig. 427), allowing for super-elevation of the track when necessary.

D

E

FIG. 423.—Types of Hangers (Brecknell, Munro, and Rogers). *A*, straight-line hanger; *B*, bridge hanger; *C*, car-shaped hanger; *D*, double pull-off; *E*, angle pull-off.

A

B

C

In practice this position of the trolley-wire would require the use of too many pull-off wires, and it is approximated by a number of straight sections, with the angle between sections limited to a minimum of about 160 degrees, in order to avoid too sudden a change in the direction of motion of the trolley-head. This point is of special importance, as

sudden changes in the direction of motion of the trolley-head not only cause excessive wear on the wire, but also increase the risk of the trolley-wheel leaving the wire. The ears used on curves should, therefore, be longer and stronger than those on straight track.

With regard to the **number of pull-offs on right-angle curves**, the general practice is to instal seven on curves of small radius (50 ft.) and nine or more on curves of larger radius, since the larger the radius of the curve the higher the speed at which it is negotiated, and therefore the change in the direction of motion of the trolley-head must be smaller.

A diagram of the **overhead construction at a double-track right-angle curve** is given in Fig. 427, and indicates the usual arrangement of the pull-off wires.

Where each end of a right-angle curve is connected to a length of straight line, it is desirable to anchor each of the straight sections, as

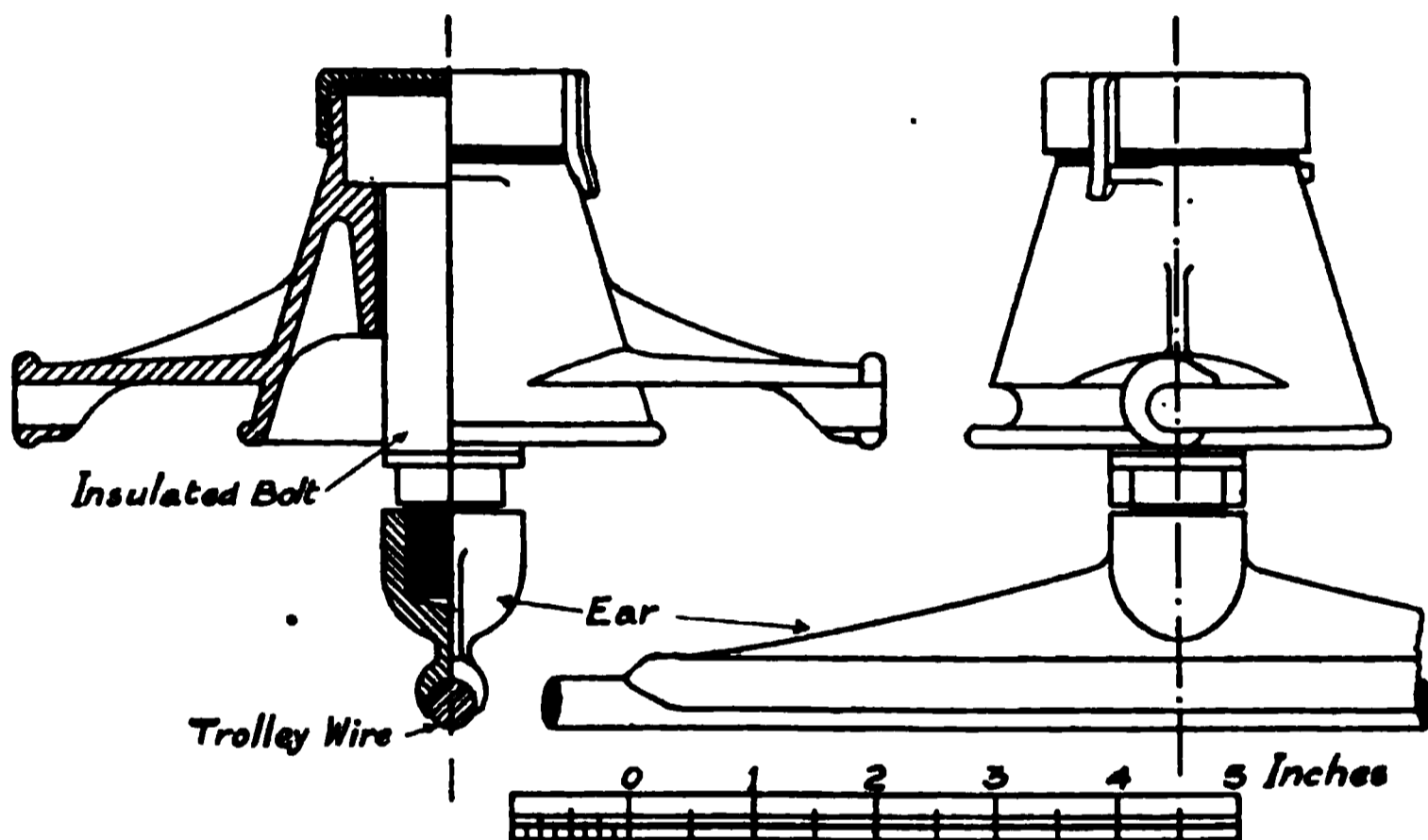


FIG. 424.—Straight-line Hanger with Insulated Bolt and Soldered Ear.

otherwise any unbalanced tension in these sections will tend to pull the curve out of shape. This method of anchoring renders the straight sections and curves mutually independent, and if an accident occurs on one of the straight sections its effects are not transmitted to the curve.

In the case of curves of very large radius, where the distance apart of the pull-offs may be 50 to 60 feet, the pull-off wire is usually attached to a bridle between adjacent poles.

At junctions, frogs and crossings are necessary for the guidance of the trolley-wheel. **Frogs** are of two types, one being fitted with a movable tongue—for use at facing points—while the other is without a tongue and is intended for trailing use only. A **two-way switch frog** is shown in Fig. 428. The tongue is maintained in one position by a spring, and is moved to the other position by a wire operated by the point controller or pointsman.

An **automatic frog** is shown in Fig. 428a. In this frog (which can be used either for facing or trailing positions) the tongue is set, for the



FIG. 425.—Types of Strain Insulators. *A*, "O.-B." globe; *B*, *C*, "Brooklyn"; *D*, longitudinal section of "Brooklyn" (*B*); *E*, *F*, *G*, *H*, porcelain "loop type" insulators (*E*, Westinghouse 600-volt insulator; *F*, General Electric 1200-volt insulator; *G*, British Insulated and Helsby Cables "Preecot" 600-volt insulator; *H*, one unit of Vedovelli-Priestley's chain type insulator).

branch line, by the trolley-pole engaging the weighted lever (at the side of the frog), and is returned to its normal position when this lever is released. For satisfactory operation the frog must be fixed so that, when a car is travelling on the branch line, the trolley-wheel is on the frog when the trolley-pole is making an angle of between 15 and 20 degrees (horizontally) with the main trolley-wire.

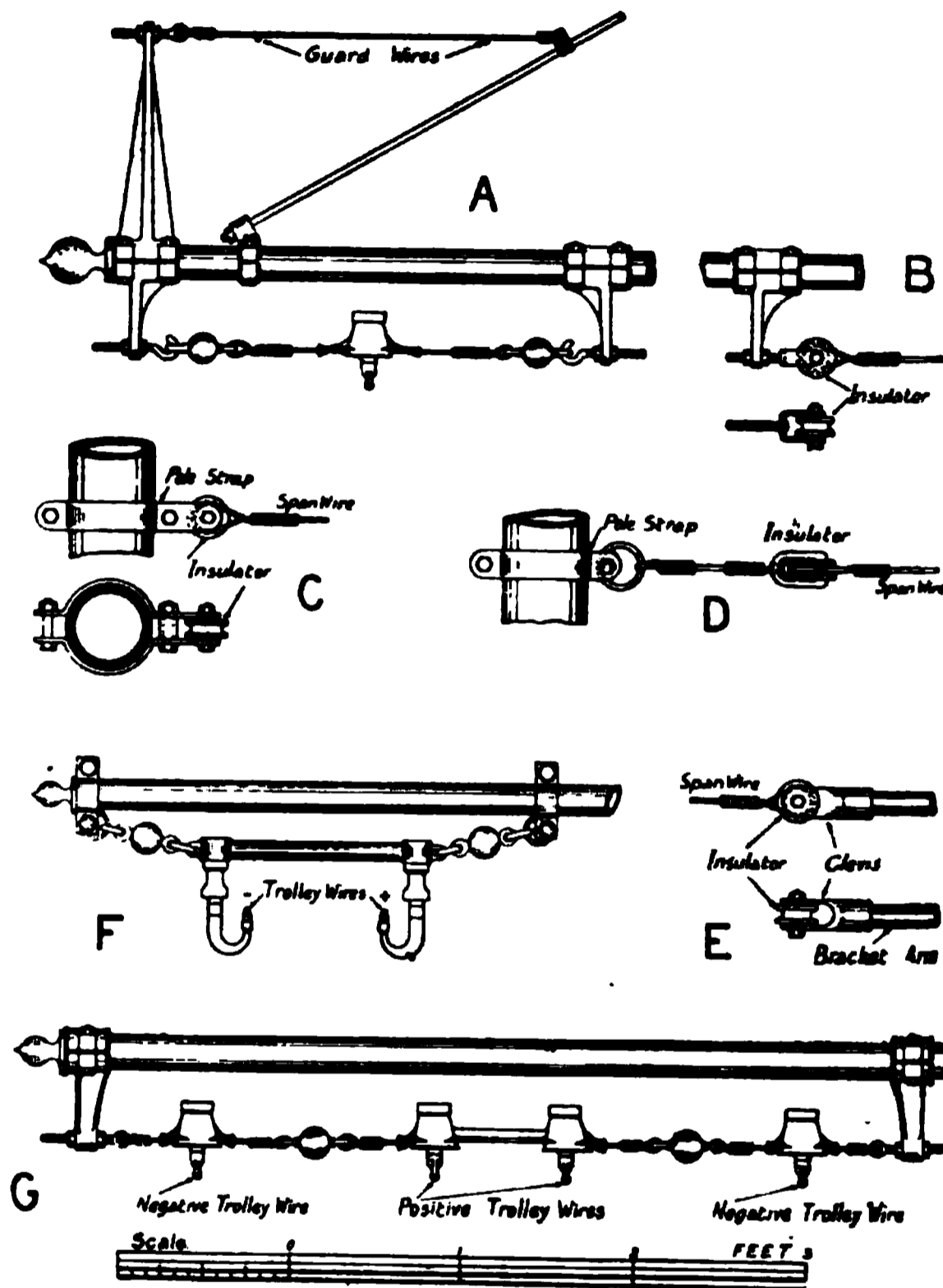


FIG. 426.—Examples of Overhead Construction. *A*, side-pole construction using "globe" insulators; *B*, side-pole construction using porcelain insulators; *C*, *D*, *E*, span-wire construction using porcelain insulators; *F*, construction for railless traction (over-running trolley system); *G*, construction for railless traction (under-running trolley system).

A **crossing** is shown in Fig. 429. The grooves in the latter are for guiding the flanges of the trolley-wheel.

The Board of Trade require the trolley-wire to be divided into sections at every half-mile, with a switch between every two sections. A **section-insulator** of the air-gap type is shown in Fig. 430. The central section *B* is insulated from the end sections *A*, *C* (to which the trolley-wires are attached), and the principal strain is taken by the insulated bolts *D*, which are in the same horizontal plane as the trolley-wire. Another section-insulator of the air-gap type is shown in Fig. 431. In

this case the end sections are connected by two insulated bolts and a strut of insulating material.

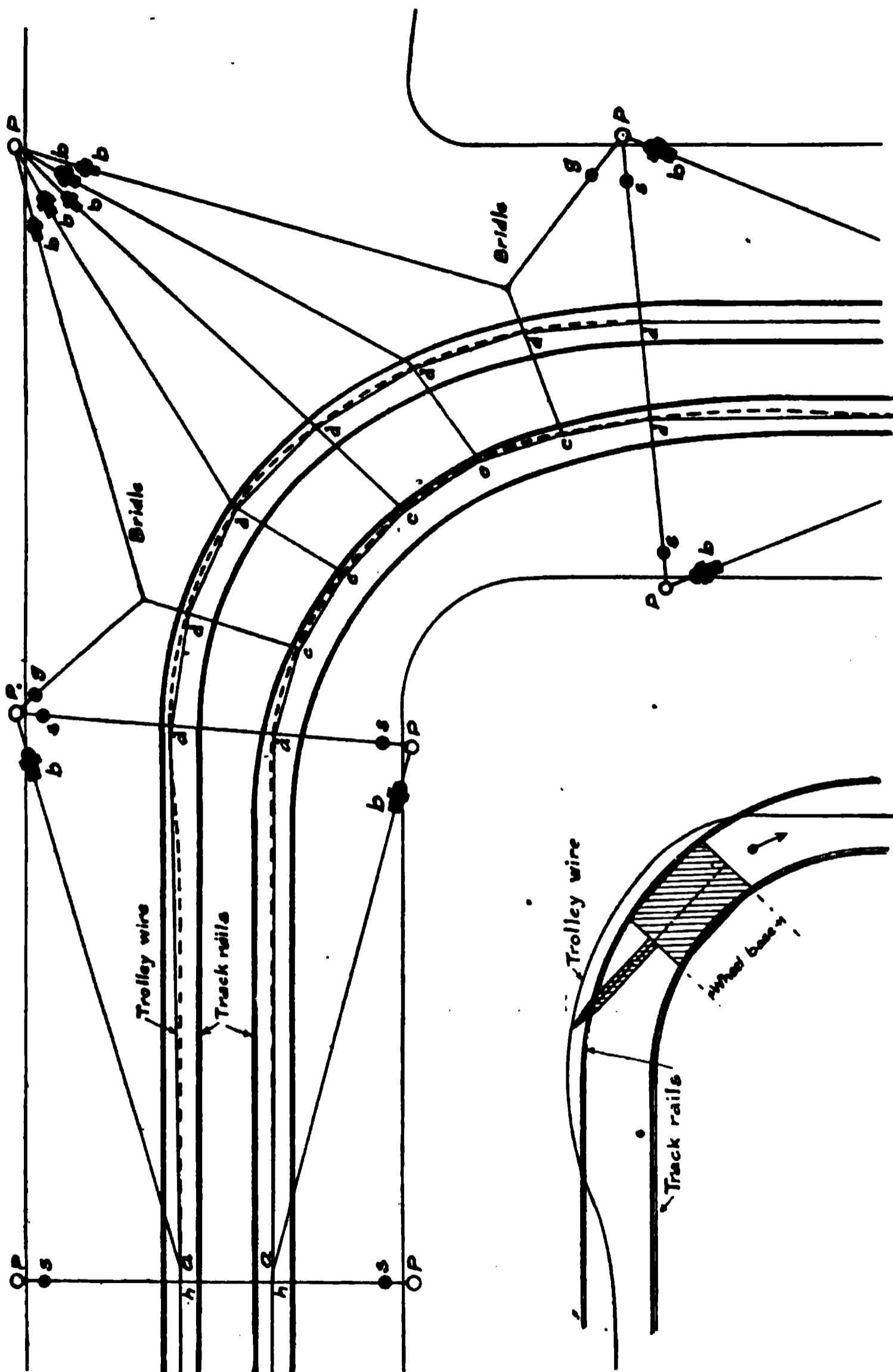


FIG. 427.—Diagram of Overhead Construction at a Double-track Right-angle Curve. *a*, anchor ear; *b*, Brooklyn strain insulator; *c*, single pull-off; *d*, double pull-off; *g*, globe strain insulator; *h*, straight-line ear; *s*, porcelain strain insulator; *P*, pole.

Views of section-insulators erected are shown in Fig. 432, in which the cables leading to the switch pillar can be seen, and also the anchoring of the trolley-wire on each side of the section-insulator.

A diagram of the overhead construction at a junction showing the

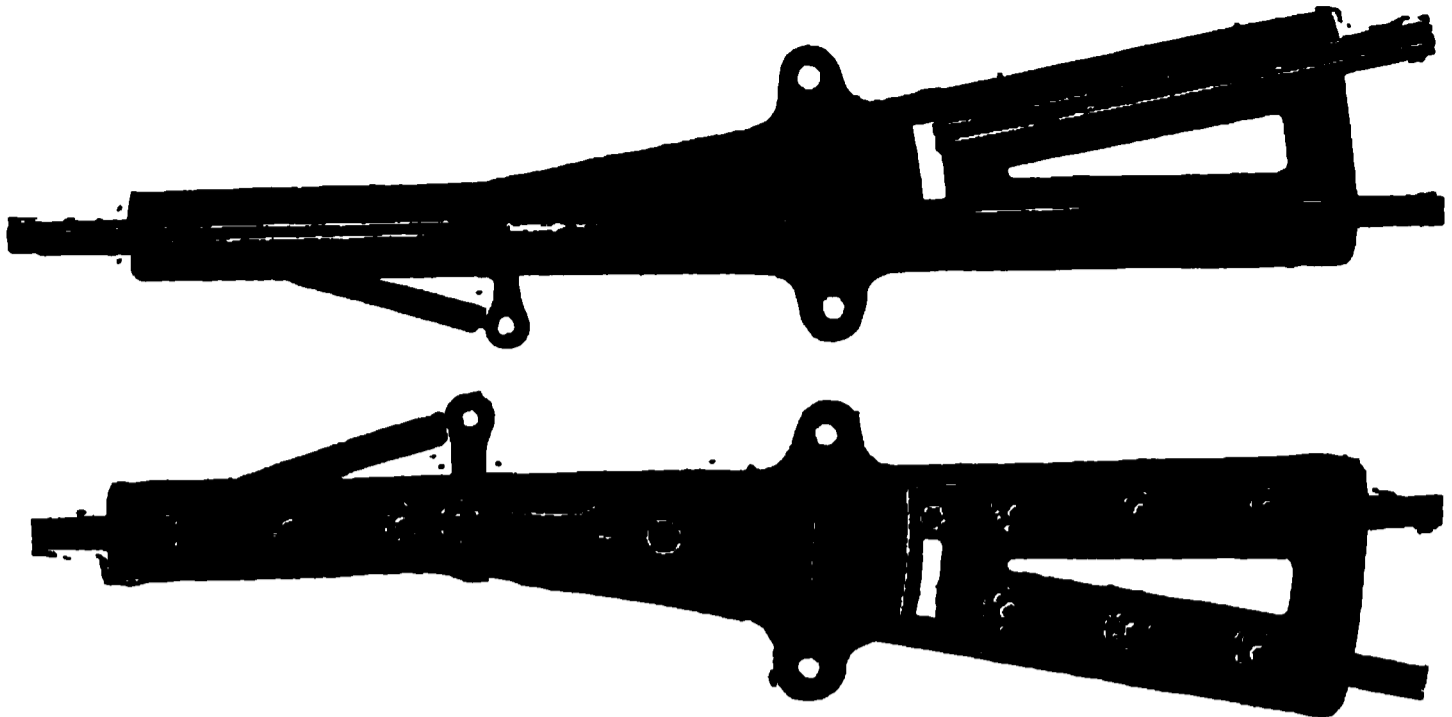


FIG. 428.—Switch Frog for Grooved Trolley-wire (British Insulated and Helsby Cables).

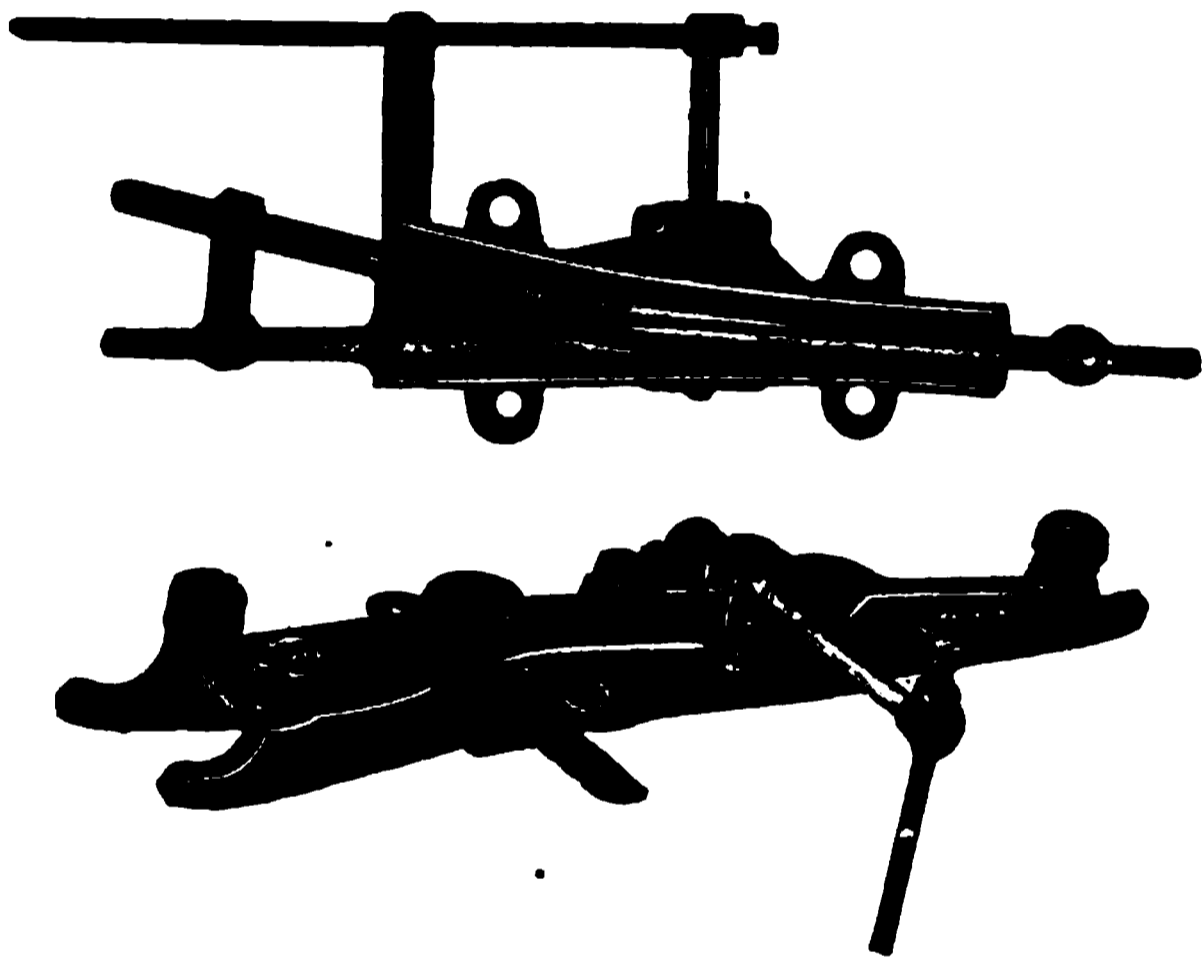


FIG. 428a.—Automatic Frog—operated by Trolley-boom (Brecknell, Munro, and Rogers).

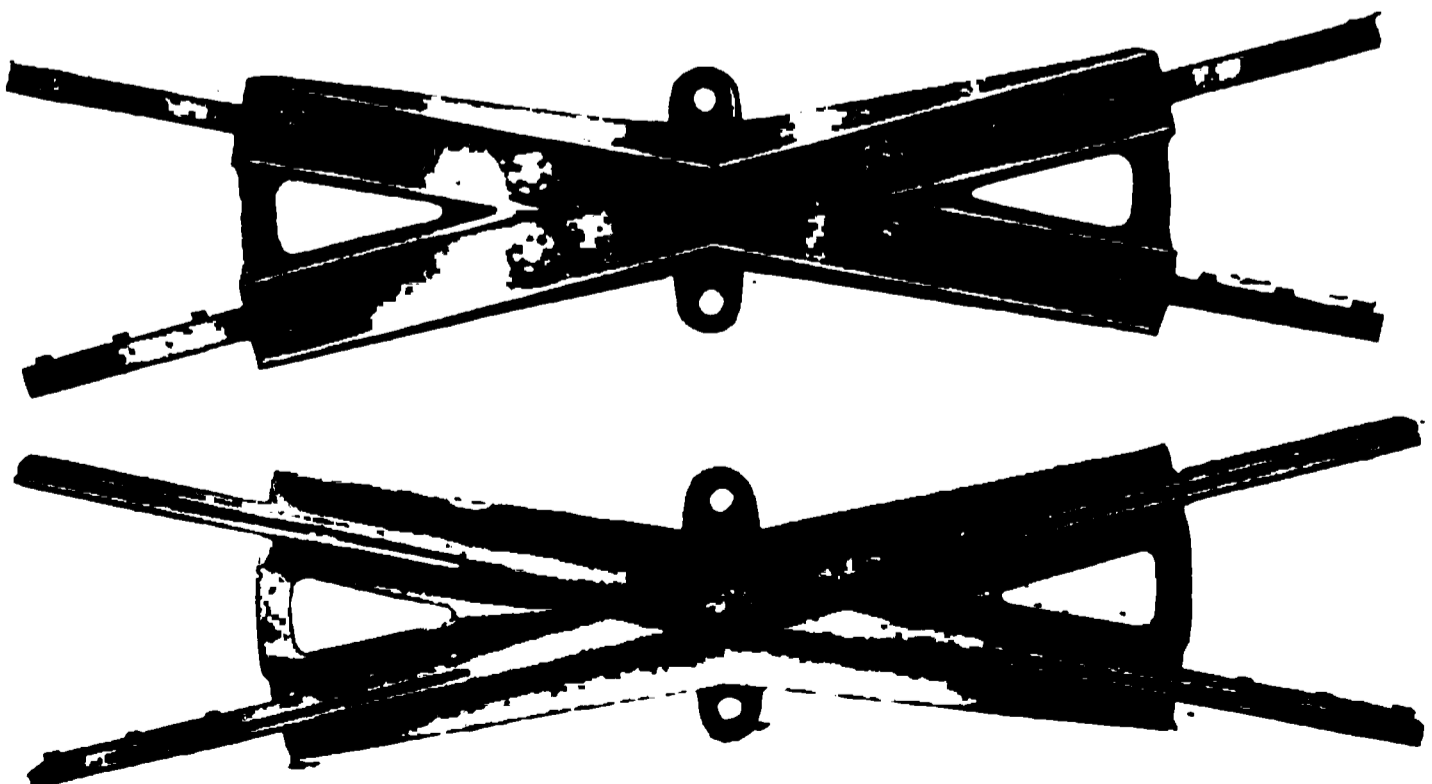


FIG. 429.—25° Fixed Crossing (British Insulated and Helsby Cables).

arrangement of frogs, crossings, and section-insulators, is given in Fig. 433. The section-insulators for the branch lines are carried on bracket arms, which are anchored to poles on each side.

FIG. 430.—Section-insulator (Brecknell, Munro, and Rogers).

FIG. 431.—Section-insulator (British Insulated and Helsby Cable).

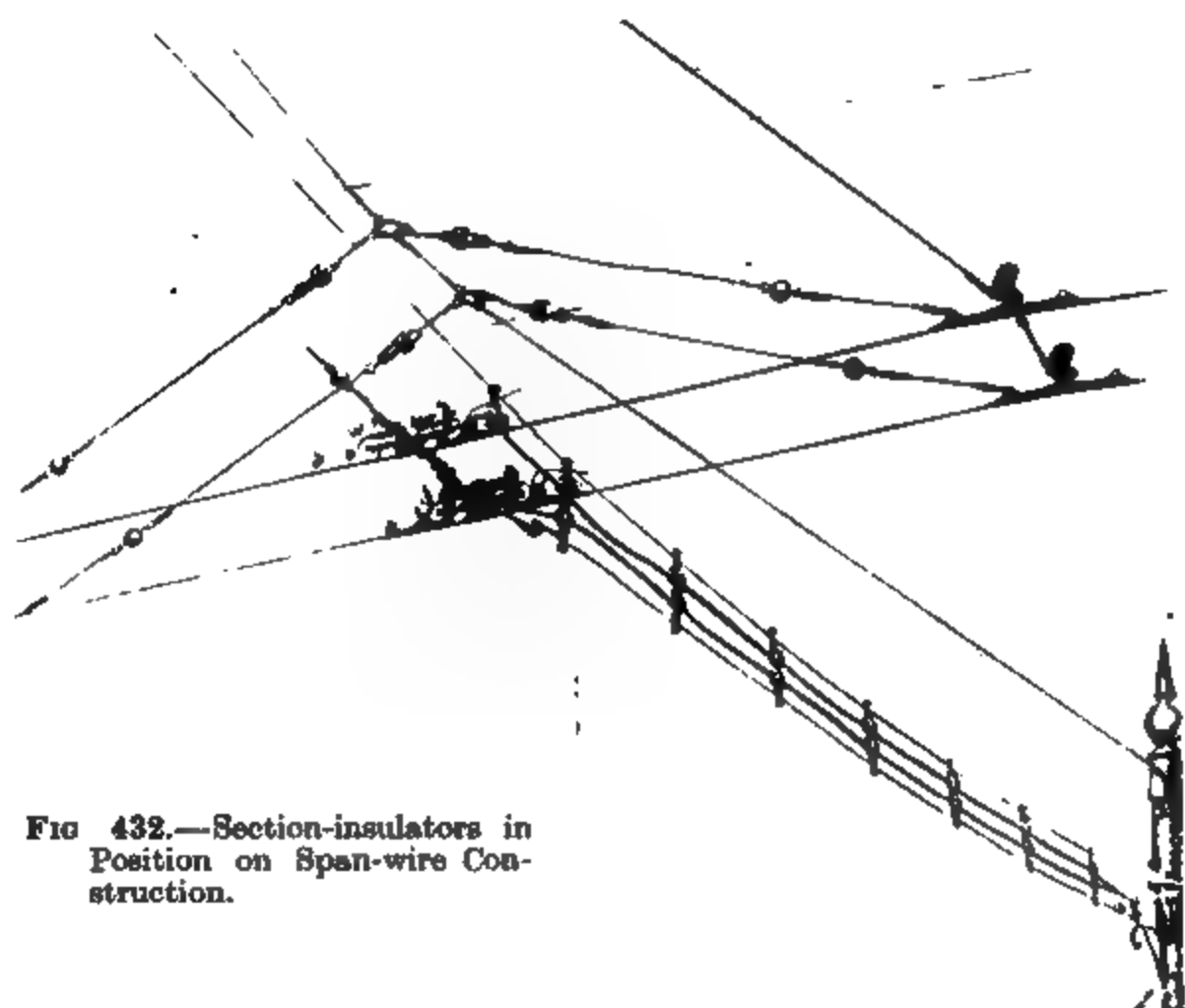


FIG. 432.—Section-insulators in Position on Span-wire Construction.

Where bare telephone and telegraph wires cross the trolley-wires, the Board of Trade require guard wires to be erected, as detailed on p. 641.

Poles are of the tubular type, and usually consist of three steel tubes, of different diameters, shrunk together with telescopic joints. The overall length is 31 ft.; the length of bottom section is 17 ft.; while the

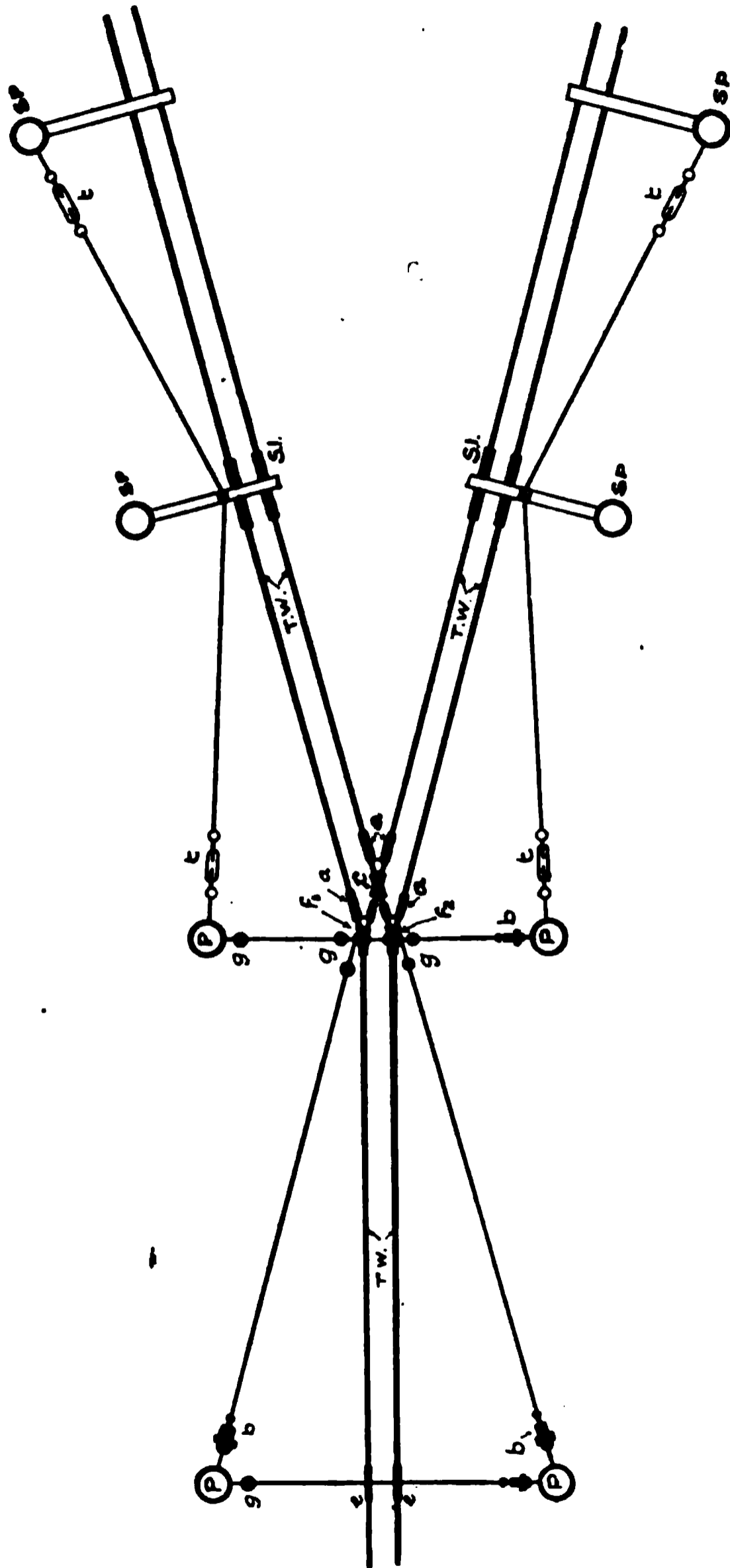


FIG. 433.—Diagram of Overhead Construction at Double-track Junction. *a*, special ears fitted with distance pieces to maintain trolley-wires in correct relative positions; *b*, Brooklyn strain insulator; *c*, crossing; *e*, straight-line ear; *f*₁, switch frog; *f*₂, trailing frog; *g*, globe (or porcelain) strain insulator; *t*, turnbuckle; *P*, pole; *SP*, side pole with bracket-arm; *SI*, section-insulator.

middle and top sections are each 8 ft. 6 in. long, and each joint is 1 ft. 6 in. long. There are three standard sizes of poles in use, viz. (1) "light," suitable for pulls up to 750 lb.; (2) "medium," suitable for pulls up

to 1250 lb.; and (3) "heavy," suitable for pulls up to 2000 lb. The "heavy" poles are only used for anchoring purposes or at curves where several pull-off wires are attached to one pole.

The **pole trimmings** usually consist of a finial, fitted into the top of the pole; two collars, slipped over the joints; and a base, ornamented to suit the requirements of the neighbourhood. The **bracket arms** of side-poles consist of steel tubing, $2\frac{1}{2}$ to 3 in. in diameter, fixed to the poles by means of collars and tie-rods. On span-wire construction it is usual to use a short bracket arm of the type shown in Fig. 426 (E).

The poles are fixed in 6 ft. of concrete, with a concrete "biscuit" 6 in. thick under the base. The thickness of concrete around the pole depends on the nature of the subsoil, and under normal conditions about 8 to 10 in. is sufficient. Each pole must be set with sufficient rake so that the tension in the span-wire will pull it vertical.

CALCULATION OF STRESSES IN TROLLEY-WIRE AND SPAN-WIRES

Relation between Sag and Tension for a Trolley-wire.—When a flexible wire is suspended horizontally and loaded only by its own weight, the wire will hang in a catenary.* If the sag is small in comparison with the span, it can be shown that the catenary is practically identical with a parabola.† Now, in tramway overhead construction, the sag in the trolley-wire rarely exceeds 1 per cent. of the span, so that the relation between the sag and the span can be expressed in the form

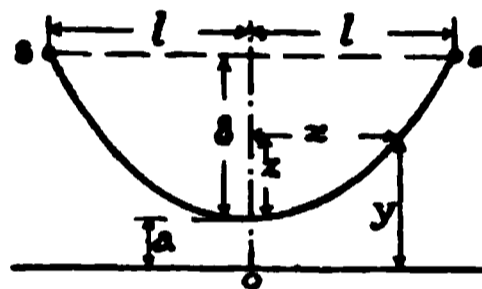


FIG. 434.

$\delta = \frac{l^2}{A}$, where δ is the sag, $2l$ is the span, and A is a constant. The constant can be determined when the weight of unit length of the wire and the tension at the lowest point (i.e. at the centre of the span in the case under

* The general equation of the catenary is—

$$y = \frac{a}{2} \left(e^{\frac{x}{a}} + e^{-\frac{x}{a}} \right) \text{ or } y = a \cosh \frac{x}{a},$$

where a is the distance from the origin to the vertex.

If z is the height of the point x, y , above the vertex (see Fig. 434), then

$$z = y - a = a \cosh \frac{x}{a} - a = a \left(\cosh \frac{x}{a} - 1 \right).$$

Expanding, we obtain

$$\begin{aligned} z &= a \left\{ 1 + \frac{\left(\frac{x}{a}\right)^2}{2} + \frac{\left(\frac{x}{a}\right)^4}{24} + \frac{\left(\frac{x}{a}\right)^6}{720} + \dots - 1 \right\} \\ &= \frac{a}{2} \left\{ \left(\frac{x}{a}\right)^2 + \frac{1}{12} \left(\frac{x}{a}\right)^4 + \frac{1}{360} \left(\frac{x}{a}\right)^6 + \dots \right\} \\ &= \frac{x^2}{2a} \left\{ 1 + \frac{1}{12} \left(\frac{x}{a}\right)^2 + \frac{1}{360} \left(\frac{x}{a}\right)^4 + \dots \right\} \end{aligned}$$

which, if the second and succeeding terms are neglected, becomes

$$z = \frac{x^2}{2a}, \text{ or } x^2 = 2az,$$

which is the equation to a parabola.

† If, in the case of a catenary, the sag is 1 per cent. of the span, then the sag of a corresponding parabola will be only ($\frac{1}{8}$ of 1 per cent.) smaller than that of the catenary.

consideration) are known. If w is the weight (in lb.) of unit length of the wire and T is the tension (in lb.), then, by taking moments about one of the supports (s , Fig. 434), we have

$$T\delta = wl \times \frac{1}{2}l,$$

whence

$$T = \frac{wl^2}{2\delta},$$

and

$$\delta = \frac{wl^2}{2T} \dots \dots \dots (44)$$

Hence the constant A in the above equation $= 2\frac{T}{w}$.

The tension T is not uniform throughout the span, but increases slightly towards the supports. With small sags, however, the variation is practically negligible, and will not be considered in our calculations.

In this country trolley-wire is usually erected with a sag of 9 in. in a span of 120 ft., at a temperature of about 65° F. Hence, applying equation (44) to these conditions, we have $\frac{l^2}{2\delta} = \frac{(60)^2}{2 \times 0.75} = 2400$, so that $T = 2400w$. From Table XXVIII (p. 508) we obtain the following values for w (the weight per foot of trolley-wire) :

Size of wire (S.W.G.)	2/0	3/0	4/0
Weight per foot (lb.)	0.367	0.419	0.484

and on substituting these values we obtain the following values for the tension :

Size of wire (S.W.G.)	2/0	3/0	4/0
Area of cross-section (sq. in.)	0.095	0.1087	0.1257
Tension in lb. (9-in. sag, 120-ft. span)	880	1005	1160
Stress (lb. per sq. in.)	9270	9240	9230

Effect of Temperature on the Sag and Tension.—A change in the temperature will produce changes in the sag and tension. The latter can be determined easily when the sag is known, but in calculating the sag at different temperatures we have to consider the elasticity of the wire.* Thus a decrease in the temperature will reduce the sag, but the increased tension, due to the reduced sag, will produce a stretching of the wire, so that the resulting change in the sag will be smaller than that obtained if the elasticity of the material were neglected. Consider a length of wire suspended between two horizontal supports at a distance $2l$ apart, and let

- L_0 = unstretched length of wire at a temperature θ° F.,
- L'_0 = unstretched length of wire at a temperature θ_1° F.,
- L = the length at a temperature θ° F., when erected with a sag δ and a tension T ;
- L_1 = the length at a temperature θ_1° F., the corresponding values of the sag and tension being δ_1, T_1 ;
- α = coefficient of linear expansion of the material ;
- E = Young's modulus of elasticity of the material ;
- a = area of cross-section of the wire ;
- w = weight of unit length of the wire.

* This was first pointed out by Professor B. Hopkinson. See *The Electrician*, vol. 46, p. 501.

Then, at a temperature 0° , the extension due to the elasticity of the wire will be $L - L_o$, and the strain * will be $\frac{L - L_o}{L_o}$. The stress in the wire will be $\frac{T}{a}$; and, as Young's modulus of elasticity = $\frac{\text{stress}}{\text{strain}}$

we have $E = \frac{\frac{T}{a}}{\frac{L - L_o}{L_o}}$, from which the unstretched length is obtained as

$$L_o = L \left(\frac{1}{1 + \frac{T}{aE}} \right) \quad \dots \dots \dots (45)$$

or approximately

$$L_o = L \left(1 - \frac{T}{aE} \right) \quad \dots \dots \dots (45a)$$

The length (L) corresponding to a sag of δ in a span $2l$ is given with sufficient accuracy by

$$L = 2l \left\{ 1 + \frac{2}{3} \left(\frac{\delta}{l} \right)^2 \right\} \dagger \quad \dots \dots \dots (46)$$

Substituting in equation (45) we obtain

$$L_o = 2l \left\{ 1 + \frac{2}{3} \left(\frac{\delta}{l} \right)^2 \right\} \left(\frac{1}{1 + \frac{T}{aE}} \right) \quad \dots \dots \dots (45b)$$

Now, if the temperature increases to θ_1 , the unstretched length becomes $L'_o = L_o(1 + \alpha(\theta_1 - \theta))$, and when the wire is erected this length will be stretched to a length L_1 , the corresponding values of the sag and tension being δ_1 and T_1 respectively.

* Strain is here considered to mean the ratio of the extension to the original length.

† The length of any curve of which the equation is known is given by

$$L = \int \sqrt{1 + \left(\frac{dy}{dx} \right)^2} \cdot dx.$$

Applying this to the above catenary, we obtain $L = a \sinh \frac{x}{a}$

Expanding, we have

$$\begin{aligned} L &= a \left\{ \frac{x}{a} + \frac{1}{3} \left(\frac{x}{a} \right)^3 + \frac{1}{5} \left(\frac{x}{a} \right)^5 + \dots \right\} \\ &= x \left\{ 1 + \frac{1}{6} \left(\frac{x}{a} \right)^2 + \frac{1}{120} \left(\frac{x}{a} \right)^4 + \dots \right\} \\ &= x \left\{ 1 + \frac{1}{6} \left(\frac{x}{a} \right)^2 \right\} \end{aligned}$$

if the third and succeeding terms are neglected.

In the case of a suspended wire, for which the span is $2l$, we have $x=0$ at mid-span and $x=l$ at end of span. Hence the length of wire in one-half of the span is given by

$$\begin{aligned} L &= l \left\{ 1 + \frac{1}{6} \left(\frac{wl}{T} \right)^2 \right\} \\ &= l \left\{ 1 + \frac{1}{6} \left(\frac{2\delta}{l} \right)^2 \right\} \\ &= l \left\{ 1 + \frac{2}{3} \left(\frac{\delta}{l} \right)^2 \right\} \end{aligned}$$

From equations (45, 46) we have

$$\begin{aligned} L_1 &= L'_o \left(1 + \frac{T_1}{aE} \right) \\ &= L_o (1 + a(\theta_1 - \theta)) \left(1 + \frac{T_1}{aE} \right), \end{aligned}$$

and

$$L_1 = 2l \left\{ 1 + \frac{2}{3} \left(\frac{\delta_1}{l} \right)^2 \right\}.$$

Combining these equations with equation (45b) we obtain

$$2l \left\{ 1 + \frac{2}{3} \left(\frac{\delta}{l} \right)^2 \right\} \left(\frac{1}{1 + \frac{T'}{aE}} \right) = 2l \left\{ 1 + \frac{2}{3} \left(\frac{\delta_1}{l} \right)^2 \right\} \left(\frac{1}{1 + \frac{T_1}{aE}} \right) \left(\frac{1}{1 + a(\theta_1 - \theta)} \right).$$

Substituting for δ and δ_1 we have

$$\left\{ 1 + \frac{1}{6} \left(\frac{wl}{T} \right)^2 \right\} \left(1 + \frac{T_1}{aE} \right) (1 + a(\theta_1 - \theta)) = \left\{ 1 + \frac{1}{6} \left(\frac{wl}{T_1} \right)^2 \right\} \left(1 + \frac{T}{aE} \right),$$

which, when simplified by neglecting the product of small quantities (such as $\left\{ a(\theta_1 - \theta) \left(\frac{wl}{T} \right)^2 \right\}$, $\left\{ \frac{T_1}{6aE} \left(\frac{wl}{T} \right)^2 \right\}$, &c.), reduces to

$$a(\theta_1 - \theta) + \frac{1}{6} \left(\frac{wl}{T} \right)^2 - \frac{1}{6} \left(\frac{wl}{T_1} \right)^2 + \frac{1}{aE} (T_1 - T) = 0,$$

or
$$a(\theta_1 - \theta) = \frac{(wl)^2}{6} \left(\frac{1}{T_1^2} - \frac{1}{T^2} \right) + \frac{1}{aE} (T - T_1) \quad \dots \quad (47)$$

From this equation we can easily calculate the change of temperature required to produce a given change in the tension. If, however, we require the tension T_1 corresponding to the temperature θ_1 , the solution is not quite so easy, since it involves a cubic equation. Thus, expanding and rearranging terms, we obtain

$$T_1^3 + T_1^2 \left(a(\theta_1 - \theta) + \frac{1}{6} \left(\frac{wl}{T} \right)^2 - \frac{T}{aE} \right) aE = \frac{(wl)^2}{6} aE$$

which may be written—

$$T_1^2 \left\{ T_1 + aE \left(a(\theta_1 - \theta) + \frac{1}{6} \left(\frac{wl}{T} \right)^2 - \frac{T}{aE} \right) \right\} = \frac{(wl)^2}{6} aE,$$

whence
$$T_1 = \sqrt{\frac{0.166aE(wl)^2}{T_1 + aE \left\{ a(\theta_1 - \theta) + \frac{1}{6} \left(\frac{wl}{T} \right)^2 \right\} - T}} \quad \dots \quad (48)$$

or
$$T_1 = \sqrt{\frac{A}{T_1 - (T - B)}},$$

where $A = 0.166aE(wl)^2$ and $B = aE \left\{ a(\theta_1 - \theta) + \frac{1}{6} \left(\frac{wl}{T} \right)^2 \right\}.$

This may be solved by assuming an appropriate value for T_1 and obtaining the value of the expression on the right-hand side, which should agree with the assumed value if the latter has been correctly chosen.*

As an **example**, suppose we require the tension in a 120-ft. span of 4/0 copper trolley-wire at temperatures of 40° F. and 100° F., having

* A slide-rule greatly facilitates the application of this method.

given that the trolley-wire has been erected with a sag of 9 in. at a temperature of 65° F.

From Table XXVIII, p. 508, we obtain

$a=0.1257$ sq. in., $w=0.484$ lb., $E=18 \times 10^6$ lb. per sq. in.,
 $\alpha=0.0000093$, and from the example on p. 522,
 $T=1160$ lb.

Hence, substituting these values in equation (48), we obtain

$$T_1=1000\sqrt{\frac{319}{T_1+21(\theta_1-65)+236-1160}}.$$

For a temperature of 40° F. we have

$$T_1=1000\sqrt{\frac{319}{T_1-1450}}=1578 \text{ lb.}$$

At 100° F. the equation for the tension becomes $T_1'=1000\sqrt{\frac{319}{T_1'-187}}$, which gives $T_1'=752$ lb.

The sags corresponding to these tensions are obtained from equation (44). Thus, at 40° F., $\delta_1=\frac{0.484 \times 60^2}{2 \times 1578}=0.552$ ft., or 6.63 in.; and at 100° F., $\delta_1'=\frac{0.484 \times 60^2}{2 \times 752}=1.16$ ft., or 13.9 in.

Summarising the results, we have

Temperature (degrees F.)	40	65	100
Sag (in.)	6.63	9	13.9
Tension (lb.)	1578	1160	752
Stress (lb. per sq. in.)	12550	9230	6000

The sag to be given to a trolley-wire at any temperature should be such that, under the severest conditions of weather, the wire is not stretched beyond its elastic limit. In tramway practice these conditions are represented by a temperature of 22° F., and a horizontal wind pressure of 20 lb. per sq. ft. If D is the diameter of the trolley-wire in inches, the wind pressure will produce a loading of $\frac{0.6D \times 20}{12}=D$ lb.*

per foot run of the wire, and this must be added vectorially to the weight per foot run in order to obtain the resultant load. Thus, if w (lb.) is the weight per foot of the wire, the resultant load per foot will be $w'=\sqrt{w^2+D^2}$, and the tension T' is given by

$$T'=\sqrt{w^2+D^2} \cdot \frac{l^2}{2\delta'} \quad . \quad . \quad . \quad . \quad . \quad . \quad (49)$$

where δ' is the sag corresponding to these conditions. This sag is, of course, to be measured in the plane of the wire, which will make an angle of $\tan^{-1}\frac{D}{w}$ to the vertical.

* The total wind pressure on a cylindrical body = 0.6 × pressure on a flat surface of the same area as the projected area of the cylinder.

Applying these conditions to the above example, we obtain

$$w' = \sqrt{0.484^2 + 0.4^2} = 0.628 \text{ lb.},$$

and from equation (48)

$$T' = 1000 \sqrt{\frac{535}{T' - 1674}} = 1830 \text{ lb.},$$

which is within the elastic limit.

Calculation of Tension in Span-wires.—The sag in a span-wire depends on (1) weight supported; (2) width of road; (3) permissible tension.

In the general case of span-wire construction we have the conditions of loading as represented in Fig. 435, in which

- W = weight of each trolley-wire and supporting device per span,
- W_1 = weight of the span-wire,
- T_s = tension in the span-wire,
- θ = inclination of the span-wire to the vertical,
- $2s$ = horizontal distance between supports of span-wire,
- $2s_1$ = distance apart of trolley-wires,
- d = sag of span-wire.

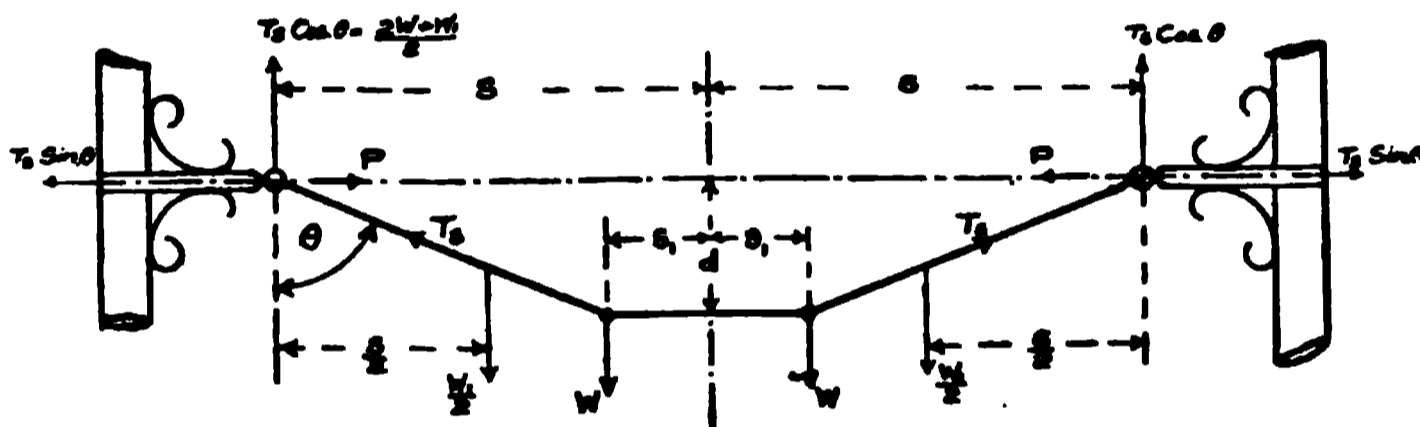


FIG. 435.—Diagram representing General Conditions of Loading of Span-wire.

By taking moments about the centre of the span we have

$$\begin{aligned} T_s \sin \theta \times d &= T_s \cos \theta \times s - \frac{1}{2} W_1 \times \frac{1}{2} s - W s_1 \\ &= \left\{ \frac{1}{2} (2W + W_1) s - \frac{1}{4} W_1 s - W s_1 \right\} \\ &= W(s - s_1) + \frac{1}{4} W_1 s. \end{aligned}$$

Writing $T_s \sin \theta = P$, we have

$$P = \frac{1}{d} \left\{ W(s - s_1) + \frac{W_1 s}{4} \right\} \quad \dots \dots \dots (50)$$

Now $T_s \sin \theta$, or P , is the horizontal pull on the pole, hence

$$T_s = \frac{P}{\sin \theta} = P \frac{\sqrt{d^2 + (s - s_1)^2}}{s - s_1} = P \sqrt{\frac{d^2}{(s - s_1)^2} + 1} = P \left(1 + \frac{d^2}{2(s - s_1)^2} \right).$$

The weights of some typical overhead fittings are given below :

Straight-line hanger with bolt	2½ lb.
Double pull-off (heavy type) with bolt	4½ „
Double pull-off (light type) with bolt	3 „
Single pull-off (heavy type) with bolt	3½ „
12-in. ear for 4/0 round trolley-wire	1 „
6-in. ear for 4/0 grooved trolley-wire	¾ „
Globe strain insulator (2 in. dia.)	¾ „

Globe strain insulator (2½ in. dia.)	1 lb.
Prescot loop type porcelain insulator (4⅜ in.)	1 „
Brooklyn strain insulator (4 in. size)	4¼ „
Section-insulator	18 „
Two-way switching frog	15 „
Two-way trailing frog	14 „
Crossing	18 „

Examples.—(1) Determine the tension in a 7/12 S.W.G span-wire when supporting two 4/0 trolley-wires 8 ft. apart, the sag in the span-

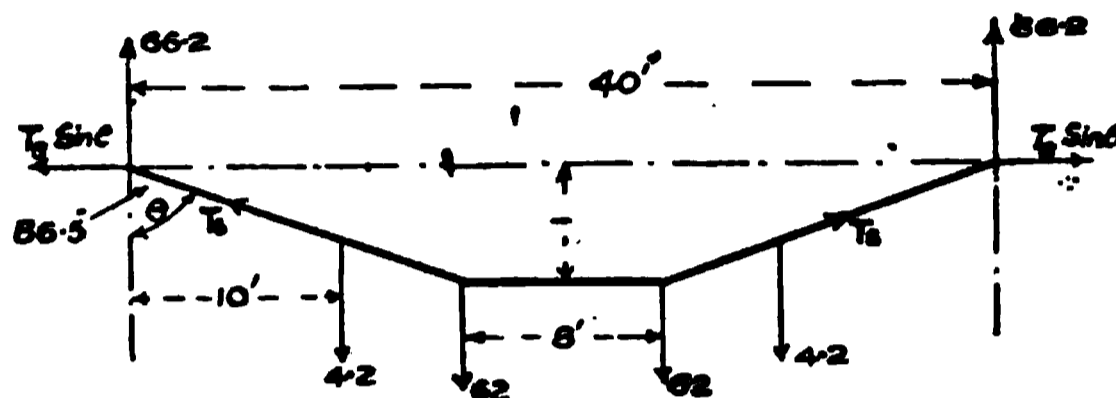


FIG. 436.—Diagram of Loading of Span-wire.

wire being 1 ft. The poles of each span are spaced at 43 ft. apart, with a distance of 120 ft. between spans, and the span-wire is attached to bracket-arms 18 in. long. We have :

$$\begin{aligned} \text{Weight of 120 ft. 4/0 trolley-wire} &= 0.484 \times 120 = 58 \text{ lb.} \\ \text{Weight of hanger, ear, \&c.} &= 4 \text{ „} \\ \hline &62 \text{ lb.} \end{aligned}$$

$$\text{Weight of 40 ft. 7/12 span-wire} = 0.21 \times 40 = 8.4 \text{ lb.}$$

A diagram of the loading is given in Fig. 436, and from equation (50) we obtain

$$P = \frac{1}{1} \left\{ 62(20 - 4) + \frac{8.4 \times 20}{4} \right\} = 1034 \text{ lb.}$$

$$\text{and } T_s = 1034 \left(1 + \frac{1}{2 \times 16^2} \right) = 1036 \text{ lb.}$$

(2) Similar conditions to above, but section-insulators fitted to the trolley-wires. We have :

$$\begin{aligned} \text{Weight of 120 ft. 4/0 trolley-wire} &= 58 \text{ lb.} \\ \text{Weight of section insulator with globe strain insulators} &= 19\frac{1}{2} \text{ „} \\ \hline &77\frac{1}{2} \text{ lb.} \end{aligned}$$

Assuming that the 7/12 S.W.G. span-wire is used, we obtain, from equation (50) :

$$P = 1283 \text{ lb. and } T_s = 1285.5 \text{ lb.}$$

If the trolley-wires are anchored in the manner shown in Fig. 432 the span-wire supporting the section-insulators will be relieved of a portion of the load. A reference to p. 520 will show that the “medium” pole will be suitable for these cases.

the pull-off wires as in Fig. 427, and the problem does not permit of such an easy solution as above, due to an incomplete knowledge of the tension in the trolley-wire, which in practice is adjusted to some arbitrary value when the line is erected. The method of calculation will perhaps be better elucidated by working through an **example**.

Thus, suppose we require the tension in the pull-off wires and the size of poles for a single 4/0 trolley-wire on a right-angle curve, of which a layout, showing the positions available for the poles, is given in Fig. 438.

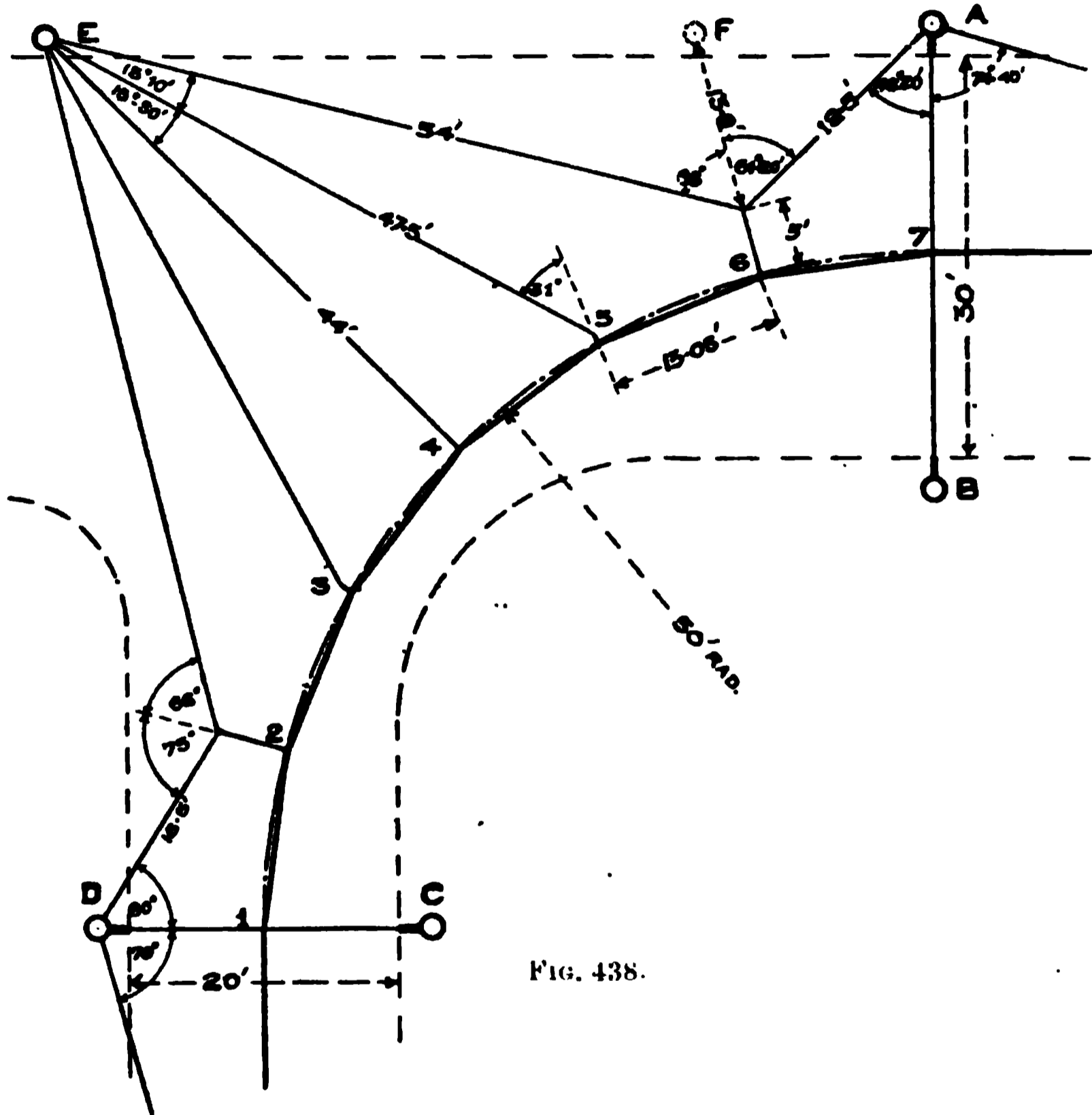


FIG. 438.

There are seven pull-offs, which are attached to the trolley-wire at a radius of 50 ft. The tension in the trolley-wire on the curve may be assumed at 700 lb. At each end of the curve there is a straight line which is suitably anchored, the tension in the anchor wire being assumed at 400 lb. The length of the first span of the straight sections is 60 ft.

The tension in the wires attached to pull-offs Nos. 3, 4, 5 can be obtained from a slight modification of equation (51). Thus, if ϕ is the angle between the pull-off wire and a radius vector produced (see Fig. 438), the horizontal pull on the pole will be given by

$$P_1 = P_1' + \frac{Tl_1}{R \cos \phi'}$$

where the first term is the pull due to the weight of trolley-wire, fittings, &c., attached to the pull-off, and the second term is the component of the trolley-wire tension in the direction of the pull-off wire. To obtain P_1' , let

W = weight of trolley-wire, ear, and pull-off ;
 W_s = weight of pull-off wire ;
 s = length of pull-off wire ; and
 d = sag in pull-off wire.

Then
$$P_1' = \frac{1}{d} \left(Ws + \frac{W_s s^2}{2} \right).$$

If we assume that 7/12 S.W.G. steel wire is used for all the pull-off and span-wires, then the weight of this wire for No. 4 pull-off will be $44 \times 0.21 = 9.2$ lb.* and $47.5 \times 0.21 = 10$ lb. for pull-offs Nos. 3 and 5. The distance between the pull-offs being 13.05 ft., we have : weight of trolley-wire, ear, and pull-off $= 13.05 \times 0.484 + 1 + 3.5 = 10.8$ lb. If the sag in the pull-off wires is 4 ft., we obtain $P_1' = \frac{1}{4} (10.8 \times 44 + 9.2 \times 22) = 169$ lb. for No. 4, and 188 lb. for Nos. 3 and 5.

Hence the tension † in pull-off wire No. 4, which is radial, will be $169 + \frac{700 \times 13.05}{50} = 169 + 183 = 352$ lb., and the tension in Nos. 3 and 5 will be $188 + \frac{183}{\cos 31^\circ} = 188 + 213 = 401$ lb.

We have now to deal with the bridles at Nos. 2 and 6, which can be done in the following manner. Consider the bridle at No. 6 replaced by a radial pull-off wire attached to a pole at F ; calculate the tension in this wire, and resolve this tension into components along the directions of the bridle.‡ In this manner we obtain 266 lb. for the tension in the

radial pull-off wire, and $\frac{266}{\cos 66^\circ + \cos 61.3^\circ} = 300$ lb. in the bridle wire.

Treating the bridle at No. 2 in a similar manner, we obtain the tension in the bridle wire as 360 lb.

The span-wires Nos. 1 and 7 now demand attention. If we assume the sag in the span-wire as 1 ft., we obtain, from equation (50), values of 128 lb. and 201 lb. for the tension in No. 1 and No. 7 respectively.

The resultant pull on pole E will be in the direction of pull-off wire No. 4, and its magnitude will be :

$$352 + 2 \times 401 \cos 15.83^\circ + (300 + 360) \cos 31^\circ = 1690 \text{ lb.}$$

The resultant pull on pole A is 540 lb., at an angle of 18° with the span-wire (straight-line side), while the resultant pull on pole D is 393 lb. at an angle of 12° with the span-wire (straight-line side).

Summarising, we have the following values for the pull on the poles : A , 540 lb. ; B , 201 lb. ; C , 128 lb. ; D , 393 lb. ; E , 1690 lb. ; while the tensions in the respective span- and pull-off wires are : No. 1, 128 lb. ;

* The effect of the inclination of the pull-off wires is neglected in the calculations of weight and tension.

† The effect of the inclination of the pull-off wires is neglected in the calculations of weight and tension.

‡ Since the bridle wire is threaded through a ring at the end of the pull-off wire, the tension in each portion of it will be the same.

No. 2 (bridle), 360 lb. ; No. 3, 401 lb. ; No. 4, 352 lb. ; No. 5, 401 lb. ; No. 6 (bridle), 300 lb. ; No. 7 201 lb. ; anchor wires, 400 lb.

Pole *E* must therefore be of the "heavy" class, while for the poles *A*, *B*, *C*, *D* the "light" class could be used.

The calculations for a double track are performed in a similar manner, but in this case the tension in the outer pull-off wires will be

$\left(P_1' + \frac{Tl_1}{R \cos \phi} \right)$, while the tension in the wire between the trolley-wires

will be $\frac{Tl_1}{R}$.

If, with the assumed value for the tension in the trolley-wire, the pull on the poles is excessive, then a lower value must be adopted and care taken that this value is not exceeded when the line is erected.

CHAPTER XXV

OVERHEAD CONSTRUCTION ON RAILWAYS

PART I. GENERAL CONSIDERATIONS

OVERHEAD construction is necessary on railways where the operating voltage exceeds 2000 volts, as this is about the maximum voltage which can be commercially applied to a conductor rail.* It is quite probable, however, that there are many places on a railway where a high-voltage conductor rail could not be used, and in these cases overhead construction must be adopted. Where the train is equipped with alternating current apparatus, the use of an overhead conductor enables a high voltage to be adopted, with the consequent saving in the capital outlay on feeders and substations.

A bow collector is generally used instead of a trolley wheel,† since with the former, no frogs or crossings are required at junctions. Moreover, this type of collector is suitable for much higher speeds and larger currents than the trolley wheel, while the chances of it leaving the trolley-wire are very remote. The bow collector, however, due to its greater inertia, requires a level trolley-wire in order that contact may be maintained between the bow and wire at high speeds.

The trolley-wire must therefore be suspended with only a very small sag, and to obtain this result without excessive tension in the wire the span must be relatively short, i.e. of the order of 10 ft. to 15 ft. It is obvious that for these short spans the method of construction adopted in tramway practice would be unsuitable, both from the mechanical as well as the electrical standpoint. However, by adopting the **catenary system**—that is, supporting the trolley-wire from another wire, suspended with considerable sag ‡ between supports of moderate span—we are able to obtain a level trolley-wire with a relatively small number of supporting structures. The wire from which the trolley-wire is supported is called the “catenary” or “messenger” wire, and by insulating this wire from the supporting structures there is no necessity for insulated hangers on the trolley-wire.

The catenary system of overhead construction has, therefore, the following advantages over the ordinary method :

* A 2400-volt conductor rail has recently been installed on the Michigan Central Railroad. See *Electric Railway Journal*, vol. 44, p. 376. 2400-volt conductor rails are now being developed for some American electrifications. See *Proceedings of the American Institute of Electrical Engineers*, vol. 34, p. 1479.

† The trolley-wheel collector is largely used on American interurban railways.

‡ The object of the large sag is to maintain a practically constant position of the trolley-wire for the range of temperature that occurs in practice.

- (1) Level trolley-wire, obtained with moderate distances between supporting structures.
- (2) Fewer insulators.
- (3) No insulated hangers.

It is interesting to note that this method of construction has only been adopted to a limited extent on three-phase railways. Although

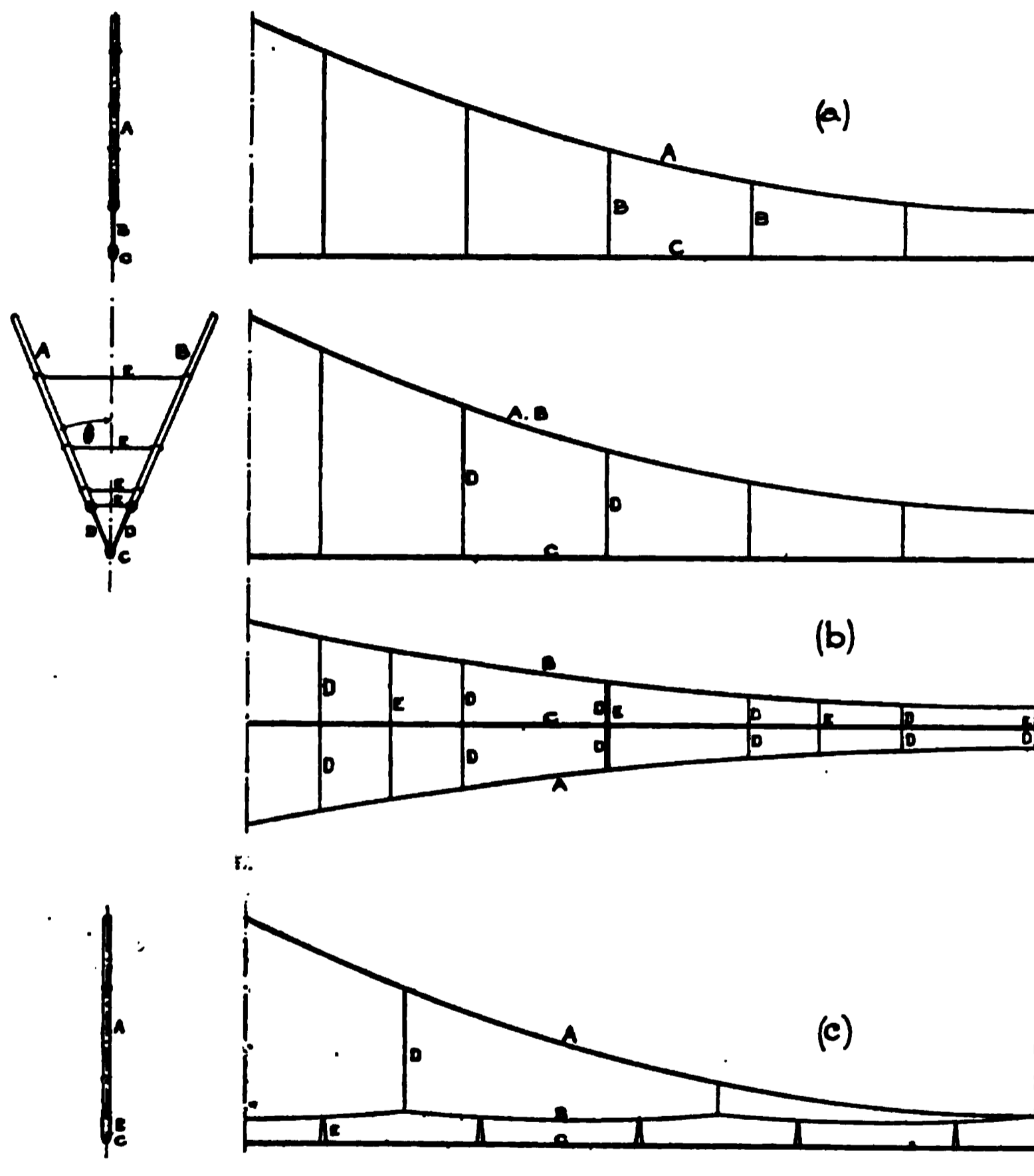


FIG. 439.—Types of Catenary Construction. (a), Single catenary; (b), double catenary; (c), compound catenary.

bow collectors are universally used, the overhead construction is generally a modified form of span-wire and side-pole construction. The probable reasons for this are: (1) The operating speeds are not very high (the maximum speed does not, generally, exceed 50 ml.p.h.). (2) Only moderately high voltage (3000 volts) is applied to the trolley-wires. (3) The complication of the overhead work at junctions would be increased enormously with catenary construction. The latter point will be appreciated after we have discussed the types of catenary

construction and given examples of the overhead construction on single-phase and three-phase railways.

The **types of catenary construction** in use may be divided into three classes: (1) the single catenary, (2) the double catenary, and (3) the compound catenary. Fig. 439(a) represents the simplest form of catenary construction, which consists of a suspended steel wire *A*, from which the trolley-wire *C* is supported by means of droppers *B*, clipped to *A* and *C* at equidistant horizontal intervals. On straight (or tangent) track the span of the catenary wire may be from 150 ft. to 300 ft., with a sag of from 3 ft. to 6 ft. respectively, while the distance apart of the droppers varies from 10 ft. to 15 ft. On curves the span must be reduced and the trolley-wire maintained in correct position by pull-off wires.

The **double catenary system** consists of two catenary wires (*A*, *B*, Fig. 439(b))—suspended from points in the same horizontal plane—from which the trolley-wire *C* is supported by the double droppers *D*. The catenary wires are connected together by cross wires *E*, so that the angle of inclination of the droppers is constant. This type of construction has a much greater lateral stability than the single or compound catenary system, and is therefore suitable for long spans.

One type of **compound catenary construction** (developed by Messrs. Siemens-Schuckert) consists of three wires, all in the same vertical plane. The upper wire *A* (Fig. 439(c)) is the catenary wire, and is insulated from the supporting structures. From this wire the intermediate wire *B* is supported by droppers, *D*, clipped to both wires, and the trolley-wire *C* is supported from the intermediate wire by the loops *E*. As originally developed, the trolley-wire was maintained under a definite tension, by means of automatic tightening gear, and the loops *E* allowed longitudinal movement of the trolley-wire to take place without straining the suspension wires.

We will now discuss the **general conditions of catenary construction** and follow these by examples of each type of construction.

The **catenary wire** is usually of stranded steel, of seven or more strands, having the following average properties:

Ultimate tensile strength.	90 tons per sq. in.
Elastic limit	40 tons per sq. in.
Modulus of elasticity	30×10^6 lb. per sq. in.
Coefficient of linear expansion (per 1° F.)	0.0000064

The **sag** of the catenary wire generally does not exceed 3 per cent. of the span, and if the wire were loaded only with its own weight, we could calculate the tension in the same manner as for a tramway trolley-wire (see p. 522), since it would be sufficiently accurate to consider the curve of the sag as a parabola.* The effect of the trolley-wire is equivalent to a series of equal weights hung from the catenary wire at equidistant horizontal intervals. If we neglect the weight of the catenary

* With a sag of 3 per cent. of the span the error in calculating the sag from the parabola equation (instead of the catenary) is 0.2 per cent., while with a 2 per cent. sag the error is 0.05 per cent.

wire, the sections between the droppers will be straight lines, and will form the envelope to the parabola $y = \frac{x^2}{2\frac{T}{W}\lambda}$, where y is the ordinate

corresponding to a distance x from the centre of the span, T the horizontal tension at the mid-span, and λ the distance apart of the weights W (see Fig. 440).

The curve * joining the points of attachment of the droppers to the catenary wire will differ slightly from this parabola,† since each section of the catenary wire is tangential to the latter.

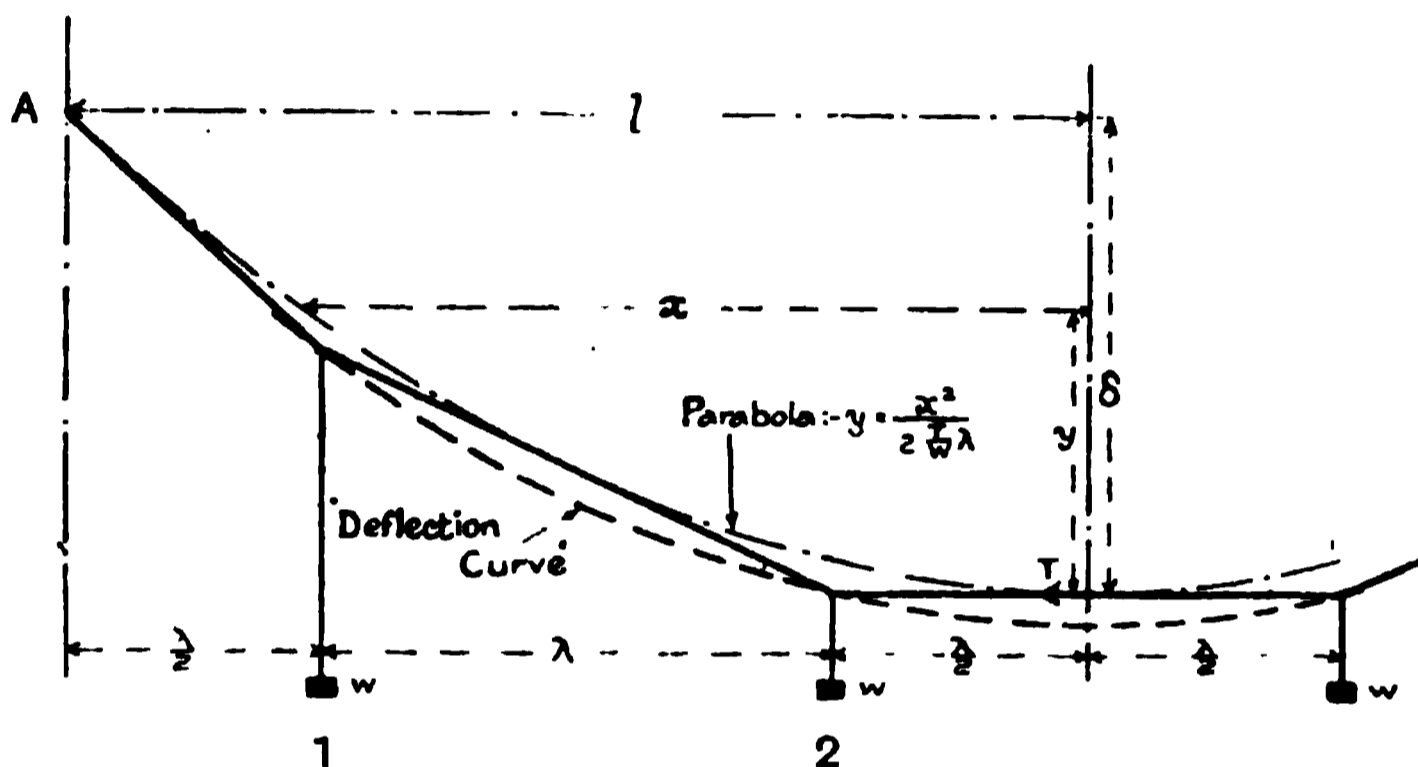


FIG. 440.

In practice the weight of the catenary wire is comparable with the weight of the trolley-wire, so that the deflection curve will be intermediate between the above curve and the parabola $y = \frac{x^2}{2\frac{T}{w'}\lambda}$ (w' being

the average weight of the trolley-wire, catenary wire, and dropper per foot of horizontal span). The sections of the catenary wire will now hang in a series of catenary curves, for which we have no particular interest, since our object is to determine the lengths of the various droppers. This may be done by the method of moments or by the application of the funicular polygon, the former being more convenient for our purpose.

Calculation of the tension in the catenary wire and the lengths of the droppers.—Consider the general case of a single catenary suspension, represented in Fig. 440, and let

* Called hereafter the "deflection" curve.

† It can be shown that each point on the deflection curve is $\left(\frac{W}{T} \cdot \frac{\lambda}{8}\right)$ vertically below the corresponding point on the above parabola.

w = weight per foot of trolley-wire ;
 w_1 = weight per foot of catenary wire ;
 w_2 = average weight of dropper and clips ;
 w' = average weight per foot of trolley-wire, catenary wire, dropper, and clips $\left[= \left(w + w_1 + \frac{w_2}{\lambda} \right) \right]$;
 $2l$ = distance (in feet) between supporting structures ;
 δ = sag (in feet) of catenary wire at mid-span ;
 z = distance (in feet) between catenary wire and trolley-wire at mid-span ;
 λ = horizontal spacing (in feet) of droppers ;
 n = number of droppers in one half of the span not including the centre one (if any) ;
 y_1, y_2 = deflection (in feet) at droppers Nos. 1, 2, &c. ;
 T = tension in catenary wire at lowest point.

The tension T is determined by considering one-half of the span and taking moments of all forces about the point of support (A , Fig. 440). Since the sag is small in comparison with the span, we are justified in assuming the weight of the catenary wire per horizontal foot of span to be identical with the weight per foot of wire. Hence w' may be considered as equivalent to the average weight of the whole suspension per foot run.

Considering an *even* number of droppers per span and taking moments about A (Fig. 440), we have :

$$\begin{aligned}
 T\delta &= (w\lambda + w_1\lambda + w_2)\frac{\lambda}{2} + (w\lambda + w_1\lambda + w_2)\frac{3\lambda}{2} + (w\lambda + w_1\lambda + w_2)\frac{5\lambda}{2} + \dots \\
 &= \{\lambda(w + w_1) + w_2\}\lambda\frac{1}{2}(1 + 3 + 5 + \dots + (2n - 1)) \\
 &= \{\lambda(w + w_1) + w_2\}\lambda\frac{1}{2}n^2 * \\
 &= \frac{l^2}{2}\left(w + w_1 + \frac{w_2}{\lambda}\right) \\
 &= \frac{1}{2}w'l^2 \dots \dots \dots (52)
 \end{aligned}$$

For an *odd* number of droppers per span we have :

$$\begin{aligned}
 T\delta &= \frac{1}{2}(w + w_1)l^2 + w_2\lambda\frac{1}{2}(1 + 3 + 5 + \dots + (2n + 1)) \\
 &= \frac{1}{2}(w + w_1)l^2 + \frac{w_2}{2\lambda}(l^2 + n\lambda^2 + \frac{3}{4}\lambda^2) \\
 &= \frac{1}{2}w'l^2 + \frac{1}{2}w_2\lambda(n + \frac{3}{4}) \dots \dots \dots (52a)
 \end{aligned}$$

The deflection at any dropper can be obtained by taking moments, about the point of the catenary wire at which the dropper is attached, and dividing by the tension T . Thus for dropper No. 1 (Fig. 440) we have (assuming an *even* number of droppers per span) :

$$Ty_1 = \frac{1}{2}(w + w_1)(l - \frac{1}{2}\lambda)^2 + w_2\lambda(1 + 2 + 3 + \dots + (n - 1)),$$

and for dropper No. 2 :

$$Ty_2 = \frac{1}{2}(w + w_1)(l - \frac{3}{2}\lambda)^2 + w_2\lambda(1 + 2 + 3 + \dots + (n - 2)),$$

* The number of terms in the series $1 + 3 + 5 + \dots + (2n - 1)$ will be n , hence the sum $= \frac{n}{2}(1 + (2n - 1)) = n^2$.

or generally :

$$Ty_m = \frac{1}{2}(w + w_1)\left\{l - \frac{1}{2}\lambda(2m-1)\right\}^2 + w_2\lambda\frac{1}{2}\{(n-(m-1))(n-m)\}^*, \quad (53)$$

where m is the number assigned to the dropper, the one nearest to the support A (Fig. 440) being No. 1.

Calling these moments M_1, M_2, \dots, M_m , we have

$$Ty_1 = M_1, Ty_2 = M_2, Ty_m = M_m$$

whence $y_1 = \frac{M_1}{T}, y_2 = \frac{M_2}{T}, \dots, y_m = \frac{M_m}{T} \quad (54)$

The lengths of the droppers will be $(y_1 + z), (y_2 + z), \&c.$, where z is the distance between the catenary wire and the trolley-wire at mid-span.

In cases where approximate results are sufficient, the deflection at each dropper can be obtained by assuming that the deflection curve is the parabola $y = \frac{x^2}{2T/w'}$, y being the deflection at a distance x from mid-span.

As an **example**, let us consider an **eleven-point single catenary suspension** having the following constants :—

Length of span ($2l$)	150 ft.
Sag at mid-span (δ)	2.5 ft. (30 in.)
Distance between catenary wire and trolley-wire at mid-span (z)	0.66 ft. (8 in.)
Number of droppers per span.	11
Spacing of droppers (λ)	13.63 ft.
Size of trolley-wire	4/0 B. & S.G. (0.46 in. dia.)
Weight per foot of trolley-wire (w)	0.641 lb.
Size of catenary wire	7/16 in. dia. (=7/9 S.W.G.)
Weight per foot of catenary wire (w_1)	0.384 lb.
Average weight of dropper and clips (w_2)	0.5 lb.
The average weight (w') of trolley-wire, catenary wire, dropper, and clips per foot run	

$$= 0.641 + 0.384 + \frac{0.5}{13.63} = 1.062 \text{ lb.}$$

Since there are 11 droppers per span, the value of n in equations (52, 53) will be 5. Hence the tension in the catenary wire at mid-span—obtained from equation (52a)—is

$$T = \frac{1}{2.5} \times \frac{1.062}{2} \times 75^2 + \frac{0.5}{2} \times 13.63 \times 5.75 = 1214 \text{ lb.}$$

* The series for the m th. dropper will be: $1 + 2 + 3 + \dots + (n-m)$, the number of terms being $(n-m)$. The sum of the series is $\frac{(n-m)(1+(n-m))}{2}$, or $\frac{(n-(m-1))(n-m)}{2}$. For an odd number of droppers per span, the last term of the series will be $n, n-1, n-2, \&c.$, instead of $n-1, n-2, \&c.$ In this case the expression for the sum of the series becomes $\frac{(n-(m-1))(n-(m-2))}{2}$, and equation (53) takes the form

$$Ty_m = \frac{1}{2}(w + w_1)\left\{l - \frac{\lambda}{2}(2m-1)\right\}^2 + w_2\lambda\frac{1}{2}\{(n-(m-1))(n-(m-2))\}. \quad (53a)$$

From equation (53a) we obtain values for M_1 , M_2 , &c., as follows:—

$$M_1 = \frac{1}{2}(0.641 + 0.384) \left\{ 75 - \frac{13.63}{2}(2 \times 1 - 1) \right\}^2 + \frac{0.5 \times 13.63}{2} \{ (5 - (1 - 1)) (5 - (1 - 2)) \} \\ = 2482$$

$$M_2 = 1593$$

$$M_3 = 897.4$$

$$M_4 = 402.5$$

$$M_5 = 102$$

The deflections are obtained by dividing these values by the tension—1214 lb.—and the lengths of the droppers will be 8 in. greater than the deflections.

A summary of the results obtained by this method and by the approximate method is given in Table XXXII below, and it will be observed that there is only a very small difference in the lengths obtained for the droppers in the two cases.

In applying the approximate method—i.e. assuming the deflection curve to be a parabola—we have:

$$T = \frac{w'l^2}{2\delta} = 1195 \text{ lb.}, \text{ and } y = \frac{x^2}{2 \times \frac{1195}{1.062}} = \frac{x^2}{2250}$$

as the equation to the deflection curve.

TABLE XXXII

Dropper No.	1	2	3	4	5	6	7	8	9	10	11
Distance from mid-span (ft.)	68.2	54.5	40.9	27.26	13.63	0	13.63	27.26	40.9	54.5	68.2
Deflection—by method of moments (ft.)	2.043	1.312	0.74	0.332	0.084	0	0.084	0.332	0.74	1.312	2.043
Deflection—by approximate method (ft.)	2.063	1.323	0.743	0.33	0.0826	0	0.0826	0.33	0.743	1.323	2.063
Length of dropper (in.)	32.5	23.8	16.9	12	9.01	8	9.01	12	16.9	23.8	32.5
Approximate length of dropper (in.)	32.8	23.9	16.9	11.96	9	8	9	11.96	16.9	23.9	32.8

In the case of a **double catenary system** the calculation of the tension, sag, &c., can be made in a similar manner, viz. by calculating the loading on one catenary wire, and treating this as a single catenary system in a plane inclined to the vertical. Thus, in Fig. 439(b), if θ is the inclination to the vertical of the plane containing the catenary wire and droppers, the vertical load on the catenary wire at each dropper will be $\left(w_2 + \frac{w\lambda}{2} \right)$ on the assumption that the droppers are looped to the clip on the catenary wire and rigidly connected to the clip on the trolley-wire. Resolving this load in the plane of the catenary wire

we obtain $\left(w_2 + \frac{w\lambda}{2}\right) \sec \theta$, while the resolved weight of the catenary wire in this plane is $w_1\lambda \sec \theta$. Hence the equation (52) becomes:

$$T\delta = \frac{l^2}{2} \left(\frac{w}{2} + w_1 + \frac{w_2}{\lambda} \right) \sec \theta \quad (55)$$

Here, δ represents the true sag in the catenary wire (*not* the apparent sag in the vertical plane), and w_2 represents one-half of the average weight of a double dropper and clips. The true lengths of the droppers will be obtained by a process similar to that given in connection with the single catenary system, the moments M_1 , M_2 , &c., being divided by $T \cos \theta$ instead of T .

In order to exemplify this method, we will calculate the **lengths of the droppers for a double catenary system**, having the following constants:—

Length of span ($2l$)	200 ft.
Apparent sag at mid-span (in vertical plane)	6 ft. 0.5 in.
Vertical distance between trolley-wire and catenary wires at mid-span	11.5 in.
Distance apart of catenary wires at supports	7 ft.
Size of trolley-wire	7/0 S.W.G. copper (0.5 in. dia.)
Weight per ft. of trolley-wire (w)	0.73 lb.
Weight of clip for trolley-wire	0.5 lb.
Size of catenary wires	12/0.088-in. steel
Weight per ft. of catenary wire (w_1)	0.282 lb.
Average weight of complete dropper and catenary wire clips	1.4 lb.
Number of droppers per span	20
Distance apart of droppers (λ)	10 ft.

The vertical distance between the highest point of the catenary wire and the trolley-wire will be found to equal 7 ft., and since the catenary wires are 7 ft. apart at the supports, the inclination to the vertical of the plane containing a catenary wire and dropper will be:

$$\theta = \tan^{-1} \frac{3.5}{7} = 26.53^\circ.$$

$$\cos \theta = 0.895.$$

$$\sec \theta = 1.117.$$

Therefore the true sag (δ) of each catenary wire is $(6.042 \times 1.117 =) 6.75$ ft., while the true distance (z) between each catenary wire and the trolley-wire at the centre of the span is $\left(\frac{11.5}{12} \times 1.117 =\right) 1.07$ ft.

Now we have: Average weight of complete dropper with clips for catenary wires and trolley-wire $= 1.4 + .5 = 1.9$ lb. Hence w_2 , in equation (55), $= \frac{1}{2} \times 1.9 = 0.95$ lb., while $w = 0.73$ lb., and $w_1 = 0.28$ lb.

Substituting these values in equation (55), we obtain the tension in each catenary wire as:

$$T \times 6.75 = \frac{100^2}{2} \left(\frac{0.73}{2} + 0.28 + \frac{0.95}{10} \right) \times 1.117,$$

whence

$$T = 612 \text{ lb.}$$

The moments $M_1, M_2, \&c.$, of the loads on one-half of one catenary wire, about the points of attachment of the droppers, are obtained by the use of equation (53). The right-hand side of the equation, however, must be divided throughout by $\cos \theta$, since the loads must be referred to the plane of the catenary wire. Thus calling the dropper next to the support as No. 1, we have :

$$\begin{aligned} M_1 &= Ty_1 = \frac{1}{\cos \theta} \left\{ \frac{1}{2} \left[\left(\frac{w}{2} + w_1 \right) \left(l - \frac{\lambda}{2} \right)^2 \right] + w_2 \lambda (1 + 2 + 3 \dots + 9) \right\} \\ &= \frac{1}{0.895} \left\{ \frac{1}{2} [(0.365 + 0.28)(100 - 5)^2] + 0.95 \times 10 \left(\frac{9 \times 10}{2} \right) \right\} \\ &= 3728. \end{aligned}$$

Similarly,

$$\begin{aligned} M_2 &= Ty_2 = \frac{1}{0.895} \left\{ \frac{1}{2} [(0.365 + 0.28)(100 - 15)^2] + 0.95 \times 10 \left(\frac{8 \times 9}{2} \right) \right\} \\ &= 2982. \end{aligned}$$

The deflections at the droppers are obtained by dividing these moments by the tension T ($=612$ lb.), while the lengths of the droppers will be 1.07 ft. greater than the deflection. Thus for dropper No. 1 we obtain

a length of $\left(\frac{3728}{612} + 1.07 \right) = 7.17$ ft.

The lengths of the remaining droppers are obtained by a similar process, and are given in Table XXXIII.

TABLE XXXIII

Dropper No.	{ 1 20	2 19	3 18	4 17	5 16	6 15	7 14	8 13	9 12	10 11
Distance from mid-span (ft.)	95	85	75	65	55	45	35	25	15	5
Moment (lb.-ft.)	3728	2982	2326	1743	1249	835	505	221	91.6	9
Deflection (ft.)	6.1	4.88	3.81	2.85	2.045	1.366	0.826	0.362	0.15	0.0147
Length of dropper (ft.) .	7.17	6.0	4.9	3.9	3.115	2.44	1.9	1.43	1.22	1.085

Effect of Temperature on the Level of the Trolley-wires.—In each of the above examples the lengths of the droppers have been calculated to give a level trolley-wire with the specified sag, on the assumption that the points of support of the catenary wire are at the same level.

The level of the trolley-wire will be affected to some extent by changes of temperature, the variation of level depending on the variation of the sag of the catenary wire with temperature. In considering the effects of temperature on the catenary wire, we shall treat the latter as a simple catenary and adopt the method given in Chapter XXIV, p. 522.

Thus, if l = length (in ft.) of half the span ;

w' = equivalent weight per ft. of catenary wire, trolley-wire, and droppers ;

a = area of cross-section of catenary wire ;

α = coefficient of linear expansion ;

E = modulus of elasticity ;

T, T_1 = tension at lowest point of catenary wire corresponding to temperatures θ, θ_1 respectively ;

δ, δ_1 = sag at mid-span corresponding to temperatures θ, θ_1 respectively ;

then

$$\alpha(\theta_1 - \theta) = \frac{(w'l)^2}{6} \left\{ \frac{1}{T_1^2} - \frac{1}{T^2} \right\} + \frac{1}{aE} (T - T_1). \quad (\text{See equation 47, p. 524.})$$

Now $\delta = \frac{w'l^2}{2T}$, and $\delta_1 = \frac{w'l^2}{2T_1}$, therefore, on substituting for T and T_1 ,

we obtain :

$$\alpha(\theta_1 - \theta) = \frac{2}{3l^2} (\delta_1^2 - \delta^2) - \frac{w'l^2}{2aE} \left(\frac{1}{\delta_1} - \frac{1}{\delta} \right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (56)$$

which gives the relation between the sag and the temperature.

The value of α for steel is 0.0000064 (per 1° F.), and E should be taken not higher than 25×10^6 lb. per sq. in. for stranded steel wires.*

If the catenary wire in the first example above is erected with the specified sag at 60° F., the sag at various temperatures, calculated from equation (56), will be :

Temperature (° F.)	24.3	42	60	78.9	98.1	118.2
Sag (in.)	26	28	30	32	34	36

This shows that the trolley-wire, as a whole, will be level only at one temperature, and at other temperatures the sections between the supporting structures will be above or below their normal position, due to the variation of the sag in the catenary wire. Thus, for the case under consideration, if the trolley-wire is level at 60° F., then, at the extreme temperatures of 22° F. and 100° F., the portion at the centre of the span will be respectively 4.25 in. above and 4.2 in. below the normal position.

Let us now consider the sections of trolley-wire between the droppers. If each dropper were definitely anchored in position, we should have conditions similar to those in tramway work, and the sag in each section, due to its own weight, would depend on the tension, temperature, &c., as explained in Chapter XXIV.

An approach to these conditions is obtained in the type of construction originally installed on some American railways, where rigid droppers, fixed to the catenary and trolley wires, were adopted.

With this type of construction, if there is any appreciable sag in the sections of the trolley-wire between the droppers, the passage of the bow collector will produce waves in the wire, and as the latter is rigidly supported at the droppers, "pounding" or "hammering" will occur

* This value for E is considerably below that (30×10^6) for hard drawn steel, the low value being due to the tightening up of the strands with the load.

at these points. On the other hand, if the trolley-wire is flexibly supported by flexible or loop droppers, the latter will accommodate themselves to any waves in the wire. It will be seen later that the latter type of construction has been adopted in recent American installations, while the rigid type has been modified by using solid steel or a silicio-bronze alloy (e.g. "phono-electric") for the trolley-wire. In this connection the following remarks—abstracted from a paper by Mr. W. N. Smith *—are of interest :—

"With the plain type of catenary construction, where no take-up devices are employed, the result is that in warm weather the sections between the hangers (droppers) become slack enough to cause the sliding bows to pound kinks into the wires at the hanger points. . . . The only remedy for this situation . . . is to pull the wire sufficiently tight so that its strain at maximum temperature will not be less than 2000 lb. for a 4/0 (B. & S.G.) wire. If the minimum tension at 100 F. is to be 2000 lb.; at 0° F. it will be about 5000 lb., and the elastic limit is reached at 5817 lb. It is to be expected that copper trolley-wire, pulled tight enough to be effective at maximum temperatures, will be likely to get pulled beyond the elastic limit in the course of a season or two. . . . These considerations may explain much of the trouble that has been experienced with plain catenary construction, using hard-drawn trolley-wire. . . .

"This warm-weather slackness can be obviated where a wire can be pulled sufficiently tight to be at a minimum of 2000 lb. at a high temperature . . . which can be done with 'phono-electric,' steel, or copper-clad steel wire.

"It is the writer's belief that without upwardly yielding hangers, it is necessary to maintain a minimum tension of at least 2000 lb.; and the only excuse for maintaining a lower tension is the ability of the trolley-wire to yield at the hangers."

The position of the trolley-wire with respect to the track should be such that the contact surface of the bow collector will be worn uniformly throughout its width. To obtain this result, it is necessary to "stagger" the trolley-wire with respect to the centre-line of the track, a stagger of 9 in. on each side of the centre-line being the usual allowance,† although the value is influenced by the design of the bow, amount of side-sway in the trolley-wire, &c.

At curves, the super-elevation of the track rails and the swing or oscillation of the coaches must be carefully considered in locating the position of the trolley-wire, since a slight tilt of the coach will correspond to a relatively large transverse movement of the bow on the trolley-wire. On sharp curves, precautions have to be taken to see that the position of the track rails, at the time of installation of the overhead construction, is maintained, as any "slewing" or alteration in the super-elevation of the track rails may result in the bow leaving the trolley-wire. This will be appreciated by Fig. 441, which represents an end view of a coach with a bow collector on a curve. The correct position of the

* "Electric Railway Catenary Trolley Construction" (*Transactions of the American Institute of Electrical Engineers*), vol. 29 (1910), p. 849.

† The zigzag of the trolley-wire should be arranged alternately on each side of the centre line of the track. For instance, in the Simplon Tunnel, the trolley-wire is staggered in sections of 1 km, the sections being arranged alternately on the right and the left of the centre line of the track. In this manner, the life of the wearing strips on the bows was trebled, the original staggering being arranged symmetrically throughout. See *The Electrician*, vol. 72, p. 58.

trolley-wire can be obtained when the super-elevation of the track,* height of trolley-wire above the track, and particulars of the coaches are known. In practice, it is more convenient to adopt the T-square method, as indicated in Fig. 442. The head of the T-square is arranged to fit

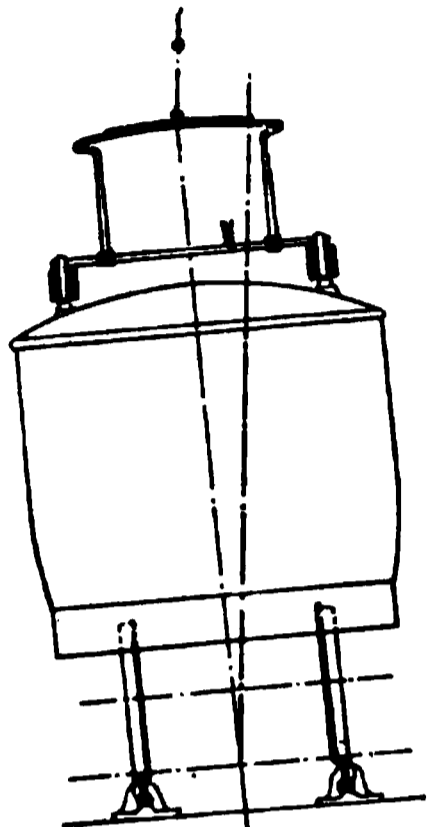


FIG. 441.
Showing tilt of coach
due to super-elevation of track.

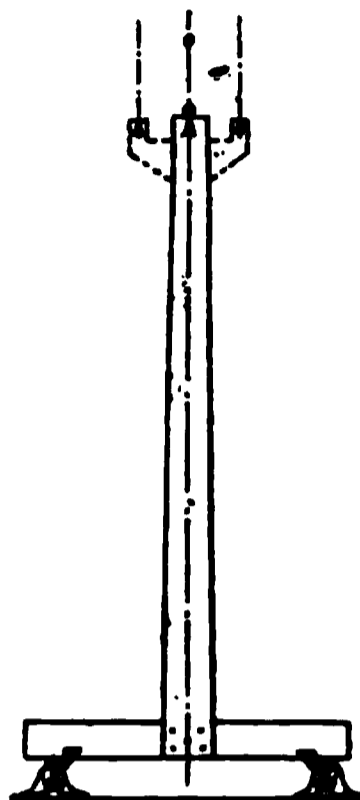


FIG. 442.
T-square for setting Trolley-wire. Extensions, shown dotted, indicate the limits of stagger.

the gauge of the track rails, and the centre-line of the track is marked on the end of the blade (which may be adjustable vertically). With this device the correct stagger of the trolley-wire can be obtained under all conditions.

PART II. TYPICAL EXAMPLES OF OVERHEAD CONSTRUCTION ON RAILWAYS

We will now describe some typical examples of overhead construction installed on railways, dealing first with the catenary system of construction, and following this with the system adopted on three-phase railways. As tunnels, bridges, &c., generally require special overhead construction, we shall consider these cases together.

Single Catenary Construction.—This type of overhead construction is adopted on a large scale in **America** for interurban roads operating at voltages between 1200 and 6000 volts. The conditions on these roads generally correspond to light traffic (*i.e.* trains of from one to three cars), and consequently do not warrant an expensive overhead installation. In the majority of cases wooden poles are used, with a bracket-arm

* The super-elevation can be obtained from formula

$$E = 0.8 \frac{V^2}{R}$$

where E = super-elevation in inches, V = velocity of train in m.p.h. and R = radius of curve in ft.

of L, T, or I section for carrying the catenary wire, while the latter is supported by porcelain insulators fixed to the bracket arm. A typical pole, bracket, and insulator are shown in Fig. 443.

The trolley-wire is maintained in the correct position with respect

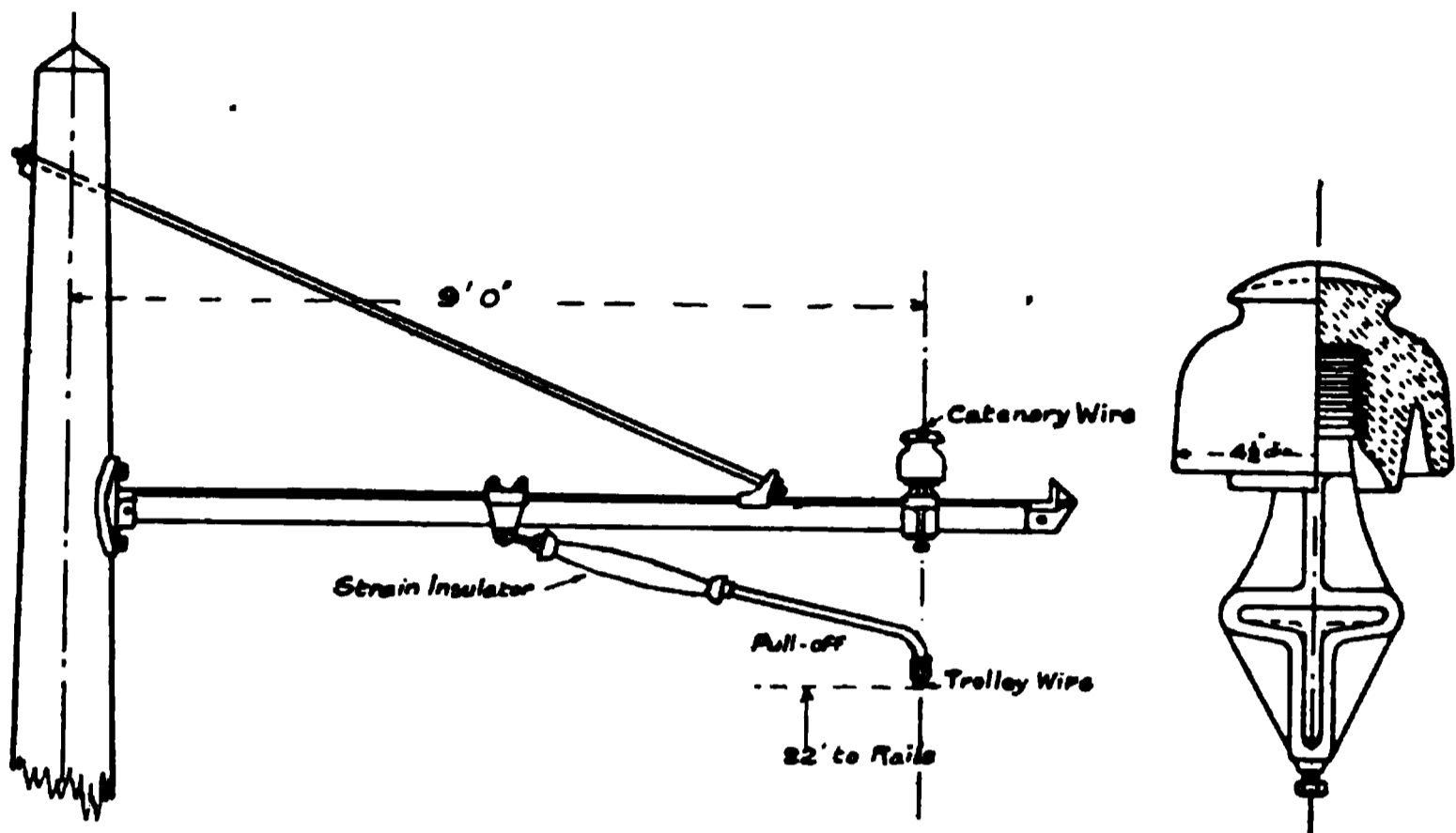


FIG. 443.—Bracket-arm Construction for 6600-volt Light Railways.

to the track by pull-offs, which were originally of the type shown in Fig. 443, but in modern installations the "spreader" type (shown in Fig. 444) has been adopted, since this gives greater flexibility to the trolley-wire. These pull-offs and steady braces are usually insulated with treated hickory wood supplemented by porcelain insulators when

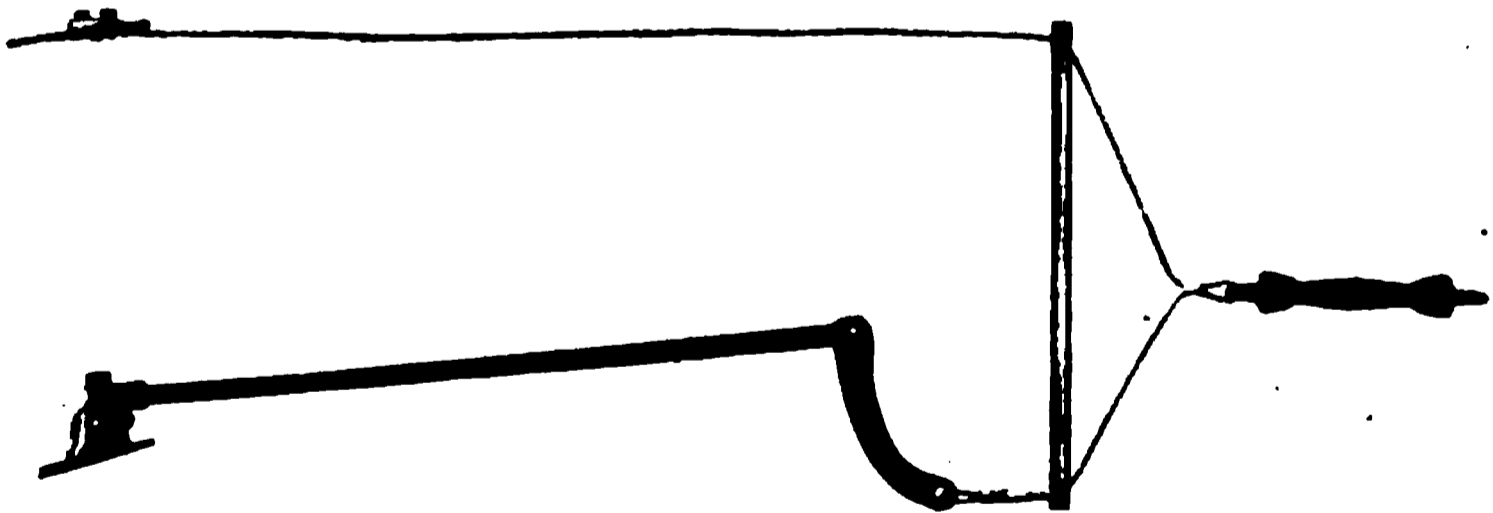


FIG. 444.—General-Electric "Spreader" Type Pull-off.

the operating voltage exceeds 6000 volts. At curves the pull-off wires are attached to bridles or pull-off poles in a manner similar to that adopted in tramway construction.

The droppers were originally of the rigid type, securely fixed to both trolley and catenary wires, but recently a loop type of dropper, fixed only to the trolley-wire, has been introduced. This type of dropper is shown in Fig. 445.

The following particulars refer to a typical construction on straight track :—

Length of span	150 ft.
Number of droppers per span	10 or 11.
Size of trolley-wire	4/0 B. & S.G. (0·46 in. dia.)
Size of catenary wire	7/16 in. dia. (=7/7 B. & S.G.)
Sag at mid-span (70° F.)	16 to 20 in.
Distance between trolley-wire and catenary wire at mid-span	6 to 8 in.
Normal height of trolley-wire above track rails	22 ft.

As a further example of single catenary construction we may consider the experimental installation of about five route miles between **Bury and Holcombe Brook** on the Lancashire and Yorkshire Railway. This line was converted to electric traction for experimental purposes in connection with the high-voltage continuous-current system. Continuous current at 3750 volts is supplied to the trolley-wire, and is collected by a collector of the pantagraph type.

Bracket-arm construction with lattice poles has been adopted on single track (except on the viaduct shown in Fig. 446) and gantry construction at places where two or more tracks are equipped. A view of the overhead construction on a viaduct is given in Fig. 446.* The length of the span on this viaduct is 400 ft., and the position is a very exposed one. In order to increase the lateral stability of the trolley-wire, auxiliary wires are run from each gantry (on either side of the trolley-wire) to points near the centre of the span, and cross-wires connect the auxiliary wires with certain droppers. The catenary wire (12/11 S.W.G.) is supported on porcelain insulators fixed to the top of the gantries (or to the bracket arms), and the trolley-wire (6/0 S.W.G., 0·464 in. dia.) is suspended from the catenary wire by light (wire) droppers spaced about 15 ft. apart. With the bracket-arm construction the normal length of span on straight track is 150 ft.

Double Catenary Construction.—This type of construction has been adopted for the suburban lines of the **London, Brighton, and South Coast Railway**. The total length of overhead equipment is equivalent to approximately 200 miles of single track, and forms the most extensive example of railway overhead construction in this country.† The electrification includes two London termini, with extensive fan-ways, and several double-track junctions, while several low bridges and tunnels have had

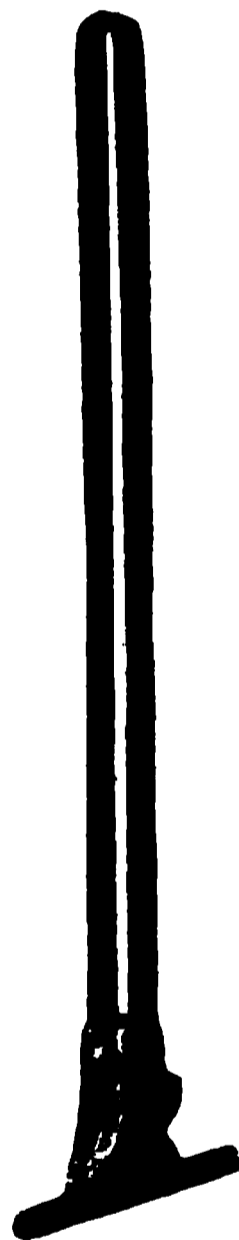


FIG. 445.—
Loop
Dropper.

* The overhead construction and entire electrical equipment were installed by Messrs. Dick, Kerr & Co., to whom the author is indebted for the photograph.

† The overhead construction was designed by Mr. Philip Dawson (see *Minutes of Proceedings, Institution of Civil Engineers*, vol. 186, p. 29, "On the Electrification of a Portion of the L.B. and S.C. Ry.") and was erected by Messrs. R. W. Blackwell & Co.

The author is indebted to Mr. Philip Dawson, M.Inst.C.E., Consulting Electrical Engineer to the L.B. and S.C. Ry., for the photographs illustrating this installation. Mr. Dawson was responsible for the design and carrying out of all the work connected with the electrification.

FIG. 446.—Overhead Construction on Bury-Holcombe Brook Section of Lancashire and Yorkshire Railway
(Dick, Kerr, & Co.).

to be negotiated.* The single-phase system is used throughout, the operating voltage being 6600 volts.

* See p. 565 for details of the overhead construction at low bridges and tunnels.

The supporting structures for the overhead work are of several types. thus, built-up lattice gantries, spanning two or more tracks, have generally been adopted for the lines in the London area, while cantilever structures, bracket-arms, centre-poles, and joist-type gantries have been used for the suburban area.

Some of these structures are shown in the views of Figs. 447, 448, 449. The spacing of the supporting structures on straight track varies from 100 ft. to 200 ft., depending on the type of structure.

Each of the catenary wires is made up of twelve galvanised steel



FIG. 447.—Four-track Gantry Construction on London, Brighton, and South Coast Railway.

strands, each 0.088 in. in diameter. The catenary wires are not continuous from span to span (as in the above examples), but each span terminates at the supporting insulators. Each section is attached to insulators, fixed to the gantries, and is provided with a turn-buckle at each end, so that the sag may be adjusted to the specified value (see Fig. 450). The sags in the adjacent spans are adjusted so that the supporting structures have only to carry the dead weight of the wires, &c.

Double insulation is used throughout the overhead equipment, and two sizes of porcelain insulators have been made to suit all requirements. The main, or gantry, insulators are of the corrugated spool type with a central steel tube, and are mounted on trunnions bolted to the gantries.

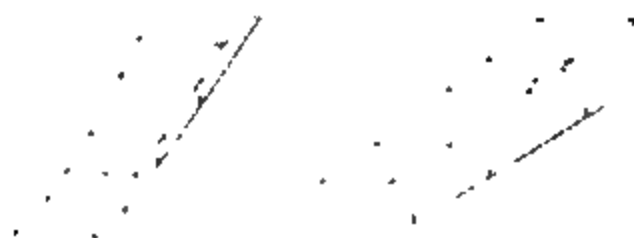


FIG. 448.—Four-track Cantilever Construction on London, Brighton, and South Coast Railway. (NOTE.—This construction is adopted where the tracks are adjacent to those of the London and South-Western Railway.)



FIG. 449 —Light Gantry Construction on Branch Line (L.B. and S.C. Railway).

The secondary, or catenary, insulators are also of the spool type, with a central steel tube, but are considerably lighter than the gantry insulators. A catenary insulator is fixed on each side of a gantry insulator, and the catenary wires are attached to straps which are clamped to the body of the insulator, as shown in Fig. 450. It should also be noted that the porcelain is subjected only to compressive stress.

The grooved trolley-wire consists of hard-drawn copper—0.5 in. in diameter (7/0 S.W.G.)—and is supported from the catenary wires by double droppers, spaced about 10 ft. apart. The droppers consist of iron wire, about $\frac{3}{16}$ in. in diameter, and are looped to clips attached to the catenary wire. Where the length exceeds 2 ft. 6 in. they are divided into two sections, linked together, as shown in Figs. 449, 450.

The trolley-wire is erected with a maximum stagger of 9 in. on either side of the centre of the track, and is maintained in the correct position by pull-offs (constructed of thin galvanised steel tube), which, under normal conditions, are fixed to the turn-buckles at the end of each span (see Fig. 450), and therefore do not require additional insulators.

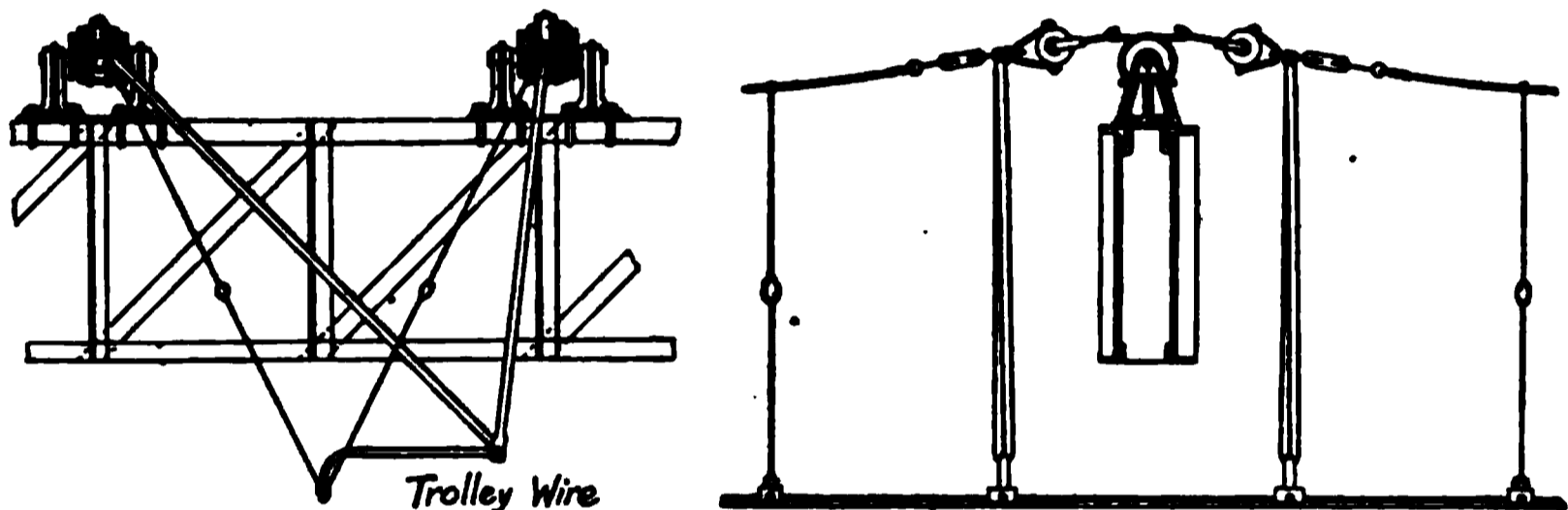


FIG. 450.—Arrangement of Insulators and Pull-off (L.B. and S.C. Railway).

This type of pull-off cannot be used at cross-overs and over-bridges, and in these cases the type with insulators, shown in Fig. 447, has been adopted. The insulators on these pull-offs are identical with those used on the gantries.

At curves, the spacing of the supporting structures is arranged so that no pull-off wires are required.

The normal height of the trolley-wire above the rail level is 16 ft., but at the London termini and at sidings, where unloading of wagons occurs, the Board of Trade required the trolley-wire to be fixed 19 ft. 9 in. above the rails (i.e. 6 ft. 6 in. above the highest portion of any coach).

At the Victoria terminus it has been necessary to instal “dead sections” under three very low bridges, as the 6-in. clearance between the structure gauge (14 ft.) of the bridges and the loading gauge (13 ft. 6 in.) was not sufficient to allow the live wires to be carried through.

The trolley-wire is divided into sections,* which are fed and controlled from switch cabins located at various parts of the system, and each section is “dead ended” or anchored at both ends. The ends of adjacent sections overlap for a short distance, and form an efficient air-insulated section-insulator.

The first American trunk line to be converted to single-phase traction

* The method of feeding the various sections is discussed in Chapter XXVI.

was the Woodlawn-Stamford section of the **New York, New Haven, and Hartford Railroad**. This line was equipped on the double catenary system with a 4/0 B. & S.G. copper trolley-wire and $\frac{9}{16}$ in. stranded steel catenary wires. At intervals of 10 ft. a triangular framework, constructed of gas-pipe, connected the trolley-wire to the catenary wires, thereby forming a somewhat rigid construction (see Fig. 451). This method of construction was not satisfactory under service conditions,* and was subsequently modified by the addition of a solid steel wire below the copper wire, supported from the latter by short clips between the

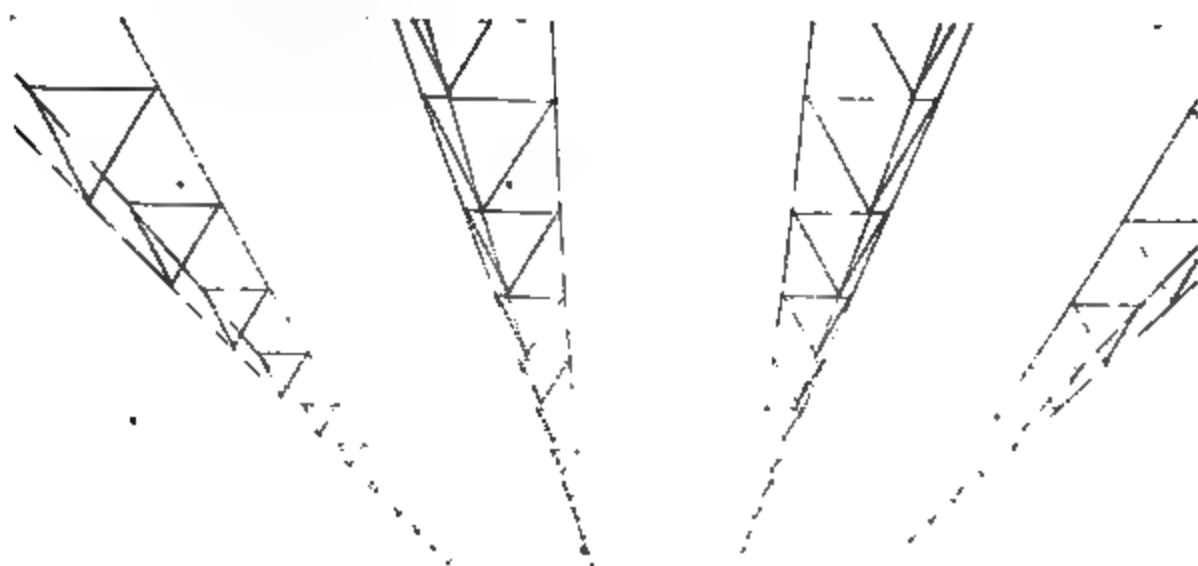


FIG. 451.—Four-track Double Catenary Construction on Woodlawn-Stamford Section of New York, New Haven, and Hartford Railroad.

droppers (see Fig. 455, p. 554). The normal distance between the gantries on straight track was 300 ft.

It is interesting to note that this combination of steel and copper has been adopted on the extensions to the New Haven system (see p. 552), where the compound catenary system has been installed.

Compound Catenary Construction.—In this type of construction we find a considerable difference between European and American practice, European installations being fitted with devices for maintaining a constant tension on the trolley-wire under all conditions of temperature, while American installations are characterised by the absence of such devices.

The principal type of compound catenary construction adopted in

* See a paper by Mr. W. S. Murray on "The Log of the New Haven Electrification" (*Transactions of the American Institute of Electrical Engineers*, vol. 27, p. 1613).

Europe is that developed by Messrs. Siemens-Schuckert, to which reference has already been made. This system, with some modifications, has been installed on the **Midland Railway Co.'s** * branch line between Lancaster, Heysham, and Morecambe, the total length of overhead

FIG. 452.—Compound Catenary Construction on Morecambe-Lancaster, Section of Midland Railway.

equipment being equivalent to 21 miles of single track. The line is operated with single-phase current at 6000 volts.

The general arrangement of the overhead construction on this line is shown in Fig. 452. The catenary wires consist of two $\frac{7}{16}$ S.W.G. steel cables, which are clipped together for nearly the whole span. At the supporting insulators the wires divide and pass through grooves in

* The Newport-Shildon (1500-volt, continuous-current) lines of the North-Eastern Railway have also been equipped on this system.

a ring fixed to the head of the insulator, so that the catenary wire is free to move longitudinally over a limited distance. The tension between adjacent spans is therefore equalised, while if a break occurs the catenary wires are not pulled down.

From the catenary wire an auxiliary wire (of $\frac{7}{13}$ S.W.G. stranded steel) is hung by droppers clipped to each at intervals of 20 ft. The trolley-wire—which is of hard-drawn copper of grooved section, equivalent to 3/0 S.W.G. (0.108 sq. in.)—is supported from the auxiliary wire by looped droppers, clipped to the former at intervals of 10 ft. These droppers are all of uniform length (about 4 in.), while those supporting the auxiliary wire are of variable length, according to their position in the span.

The catenary wires are insulated from the gantries by porcelain insulators of the triple petticoat pin type, supplemented by spool type insulators on either side.*

At the stations the gantries consist of built-up lattice structures (see Fig. 452), but at other parts of the line a light structure consisting of two angle-irons carried on wooden poles is adopted.

The trolley-wire and the auxiliary wire are anchored laterally at each gantry by a pull-off, which is clipped to the trolley-wire and hinged to the gantry. This design of pull-off, together with the loop-type droppers, allows longitudinal movement of the trolley-wire, independent of the auxiliary wire, and does not restrict the flexibility vertically.

In accordance with the standard practice of Messrs. Siemens-Schuckert, the line was originally fitted with automatic tightening devices.† This gear has been discarded, as only a very small movement of the tightening weight occurred in practice.

In view of the successful operation of the railways on which no automatic tightening gear has been installed, it is apparent that such devices are not absolutely necessary, while the additional complication of the overhead work is not warranted by the results obtained.‡

As a contrast to the above system of construction we will consider the latest type of catenary construction installed on the **Harlem River and Westchester** branches of the New York, New Haven, and Hartford Railroad. Typical views of the construction on straight and curved track are given in Figs. 453, 454.§

Two catenary wires, in addition to the trolley-wire and an auxiliary wire, are erected over each track. The upper catenary wire is a $\frac{7}{8}$ -in diameter stranded steel cable, and serves as the main supporting cable for the other wires. It is clamped directly to the top of the gantries, which are spaced 300 ft. apart on straight track and a minimum of 200 ft.

* The spool type insulators were not included in the original installation.

† For views of overhead constructions with these devices see *The Electrician*, vol. 68, p. 461; *The Engineer*, vol. 114, p. 172.

‡ In a paper on "The Electrification Schemes of the Chemin de fer du Midi," Monsieur E. J. Jullian states: "It is clear from these tests that the simplest overhead equipment is the best, for almost all accidents are due to the faulty working or breaking of apparatus introduced to obtain a better compensation or a greater flexibility for the line, and the efficiency of such apparatus is in general very doubtful" (*Journal of the Institution of Electrical Engineers*, vol. 51, p. 560).

§ The author is indebted to Mr. W. S. Murray for the photographs of the New Haven electrification. For detailed drawings of the overhead construction see Mr. Murray's paper on "Trunk Line Electrification" (*Transactions of the American Institute of Electrical Engineers*, vol. 30, p. 1437).

FIG. 453.—Four-track Compound Catenary Construction on Straight Track (New York-Westchester Section of N.Y., N.H., and H.R.R.).

FIG. 454.—Four-track Compound Catenary Construction on Curved Track (New York-Westchester Section of N.Y., N.H., and H.R.R.).

on curves. Two 3-in. "I"-beams, weighing $5\frac{1}{2}$ lb. per ft., are clamped to each span of the supporting cables so as to span the tracks. These I-beams are spaced 150 ft. apart on straight track, and carry the insulators from which the main catenary wires are suspended (see Fig. 454). The insulators are of the double petticoat type, and will withstand a dry test of 110,000 volts, the operating voltage being 11,000. The main catenary wire is a $\frac{1}{2}$ -in. diameter stranded steel cable, from which a 4/0 B. & S.G. grooved copper wire is suspended by rigid droppers or hangers spaced 10 ft. apart, the hangers being adjusted so that this

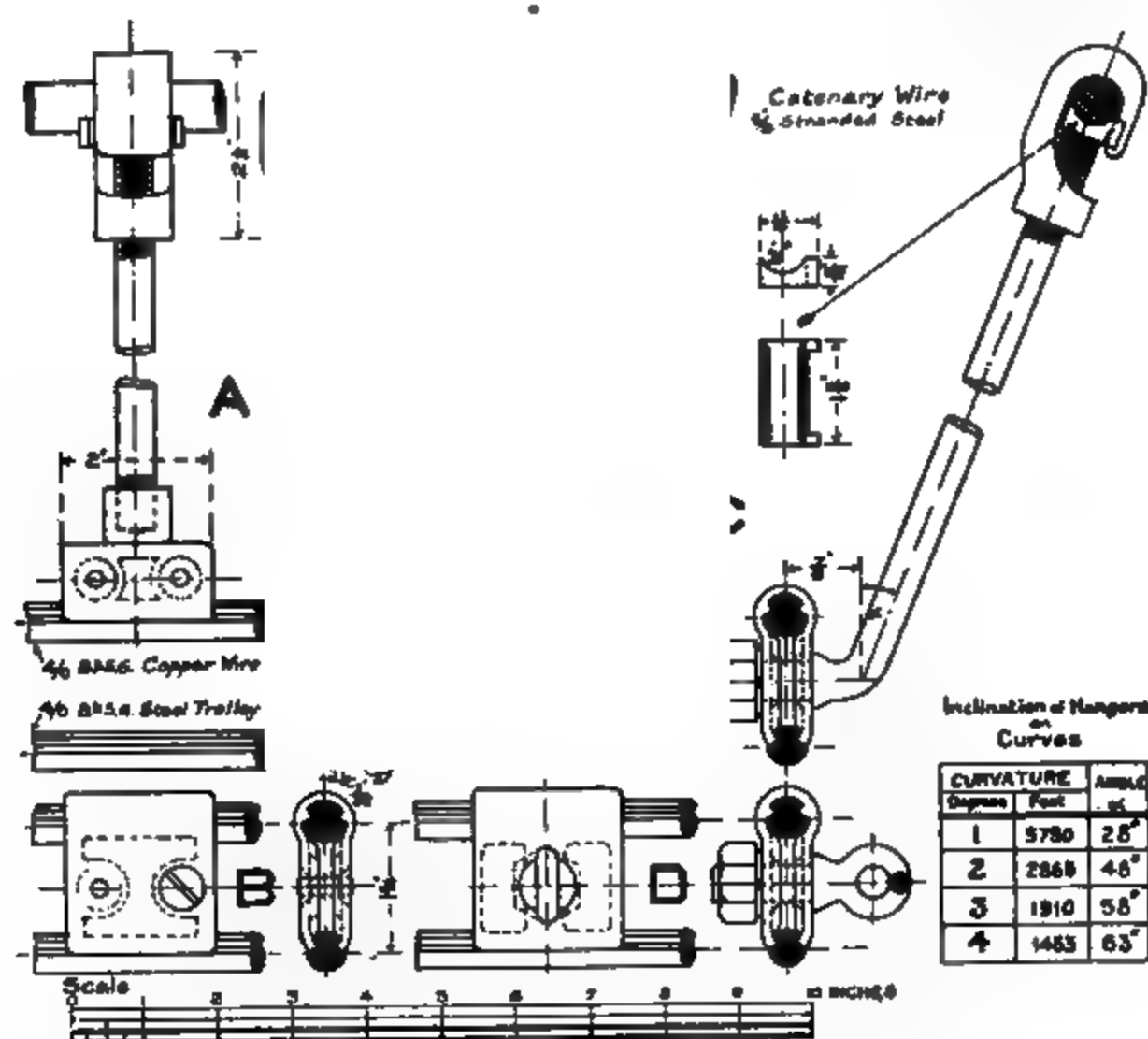


FIG. 455.—Details of Hangers and Clips for N.Y., N.H., and H.R.R. Compound Catenary Construction. A, hanger for straight track; B, intermediate clip; C, inclined hanger for curved track; D, pull-off clip.

wire is horizontal. A 4/0 B. & S.G. grooved steel wire is used as the trolley-wire, and is clipped to the auxiliary wire at points midway between the hangers.

The trolley-wires are erected approximately over the centre of each track, and on curves the alignment is maintained by the use of inclined hangers attached directly to the clips. The hangers are designed so that, when attached to the catenary wire and projecting towards the centre of the curve, the trolley-wire will follow the centre of the track. The angle of inclination varies with the radius of the curve,* and the length, of course, varies with the position of the hanger. By connecting the horizontal projection of the hanger directly to the clip attached to

* The variation of the inclination of the hangers is shown in Fig. 456.

the trolley and feeder wires, the latter are maintained in a vertical plane. These hangers and clips, together with those used for straight track, are shown in Fig. 455. Pull-off wires are only used on curves sharper than 4 degrees (1433 ft.).

All the overhead wires are sectionalised at intervals of about three miles, special anchor gantries of heavy construction being installed for this purpose (see Fig. 485, p. 597). The main supporting cables and

FIG. 456.—Construction at Reverse Curve on Norfolk and Western Railway.

the catenary cables are anchored to each side of the gantry, while the trolley-wires are run through, and are anchored to the catenary wires in the adjoining sections. The trolley-wires belonging to the same track are kept a short distance apart when passing under the gantry, and are insulated from the catenary cables to which they are anchored. In this manner a very effective air-insulated section-insulator is formed.

A simplified form of compound catenary construction has been adopted for the electrification of the **Norfolk and Western Railway**.* The upper

* The Westinghouse Co. (to whom the author is indebted for the illustrations of the overhead construction) were responsible for the electrical installation on this railway.

catenary wire in the construction illustrated in Figs. 453, 454 is dispensed with, and the main catenary wire is supported from the gantries, which, in this case, are of light tubular construction, and are spaced about 150 ft. apart on straight track. A view of the construction at a reverse

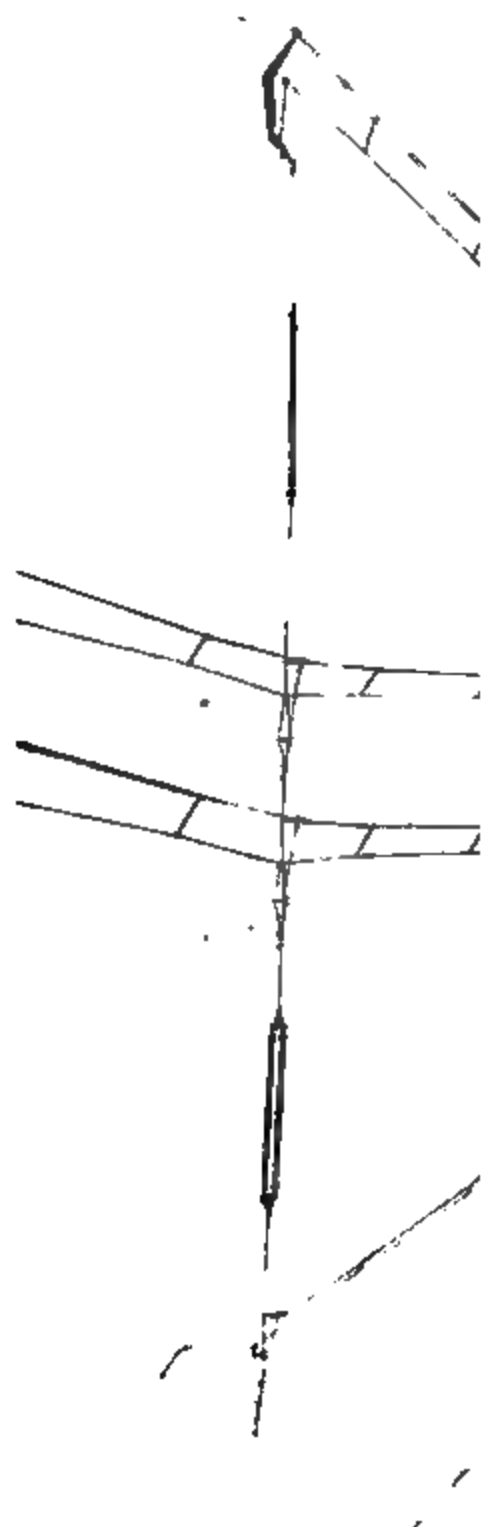


FIG. 457.—Cross Catenary Construction at Freight Yard on Norfolk and Western Railway.

curve is shown in Fig. 456. This view shows clearly the variation of the inclination of the hangers, the latter being of similar design to those adopted for the construction illustrated in Fig. 455. At sharp curves, pull-off wires are adopted, as shown in Fig. 456.

The overhead construction on the Norfolk and Western Railway possesses the special feature that only one type of insulator is used, this



FIG. 458.—Cross Catenary Construction at Large Freight Yard (N.Y., N.H., and H.R.R.).

being the standard suspension-type insulator * adopted for overhead transmission lines. The operating voltage is 11,000 volts, and three insulators are connected in series.

• **Cross Catenary Construction.**—In some cases, where a large number of tracks have to be spanned —e.g. at goods yards, train-shed fan-ways, &c.

FIG. 459.—Single Catenary Construction on the Lecco-Calolzio-Scambio Section of the Italian State Railways.

—the catenary wires are suspended from transverse span-wires, which are erected with considerable sag between towers on each side of the track. By this method, the heavy top girder, which would be required

* For data of this type of insulator see *Transactions of the American Institute of Electrical Engineers*, vol. 30, p. 2303; vol. 31, pp. 907, 2143; vol. 33, pp. 1721, 1731; *Proceedings*, vol. 34, p. 1425.

in gantry construction, is dispensed with, but higher towers are necessary on account of the sag in the span-wire.

Views of typical cross-catenary construction are shown in Figs. 457, 458, the former figure illustrating the construction at curved track (on the **Norfolk and Western Railway**), and the latter figure illustrating the construction at straight track. The view in Fig. 458 shows a portion of the **Oak Point Yard** (of the New Haven Railroad), where approximately 42 miles of track are electrified.

In each case the main catenary insulators are suspended from the span-wires by droppers of various lengths, so that the insulators are in the same horizontal plane. Each span-wire is provided with turnbuckles, which are attached directly to the towers. Lateral stability is obtained by horizontal steady-wires, which are insulated from the towers and from the catenary and trolley-wires.

Fig. 458 also illustrates some examples of **bow deflectors**, which are necessary at junctions in order to provide a smooth passage for the bow when crossing from one wire to another. The type of deflector shown in the figure consists of a light angle-steel framework, which is supported between the converging trolley-wires, so that the lower edges of the longitudinal members are level with the trolley-wires. The bow collector is therefore provided with a continuous path of contact, and fouling of the wires is thereby prevented.

OVERHEAD CONSTRUCTION ON THREE-PHASE RAILWAYS

From the above descriptions of overhead construction on the catenary system, it will be realised that at double-track junctions and terminal station fan-ways the overhead wiring is somewhat complicated. If each track had to be equipped with two trolley-wires at different potentials, the complication would be increased very considerably, for we should have to separate each of the catenary wires as well as the trolley-wires. Under these circumstances it is not surprising that the above systems of construction have only been adopted to a limited extent for three-phase railways, where two overhead conductors are required.*

In Fig. 459 is given a view showing the type of single catenary construction installed by the **Società Italiana Westinghouse** on a portion of the **Italian State Railways**. Vertical flexibility of the trolley-wire is obtained by a parallel-motion linkwork. This linkwork also provides the necessary lateral stability for the trolley-wire.

Generally the operating voltage of three-phase railways does not exceed 3300 volts, and, with one exception (the Cascade Tunnel, U.S.A.),† bow collectors are universally adopted. At this voltage it is practicable to use insulated hangers, suspended from span-wires in a manner similar to that adopted for side-pole construction on tramways, and in order to avoid too large a sag in the trolley-wire it is necessary to adopt short spans. The weight to be supported from the bracket-arm is therefore small, and a light pole and bracket-arm can be adopted. The light poles and bracket-arms are a characteristic feature of Continental three-phase railways, and form a striking contrast to the built-up structures on some single-phase railways.

* The cross-catenary system has been used to some extent in cases where a large number of tracks have had to be spanned.

† The operating voltage for the Cascade Tunnel electrification is 6600 volts.



FIG. 460. A 16-meter Bachof arm for four tracks at Sompseeluegna.

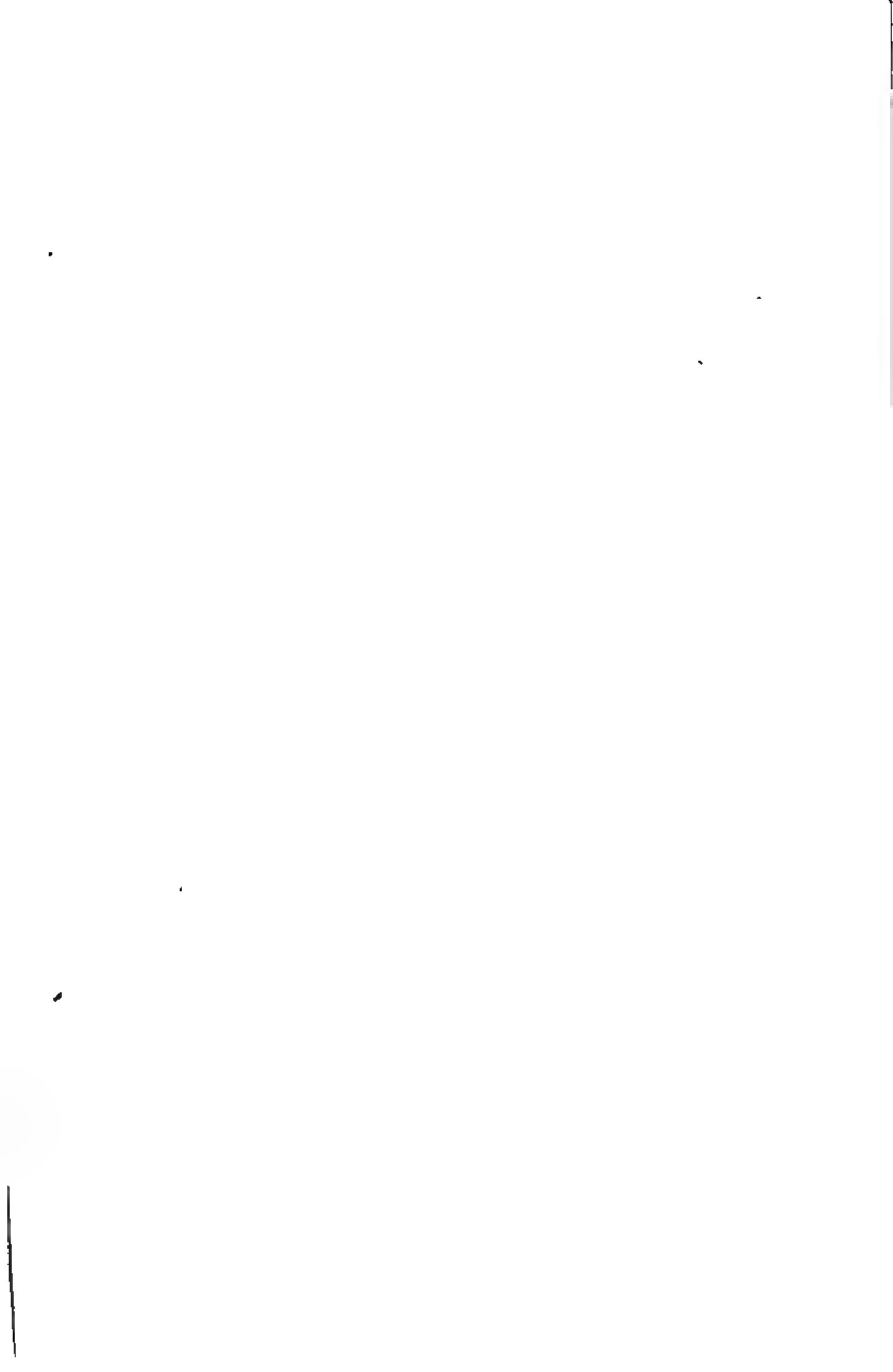


FIG. 462.—Overhead Construction at Group of Tracks at Sampierdarena

Typical views of the overhead construction on the **Giovi-Genoa** lines of the Italian State Railways and the **Simplon Tunnel** line are given in Figs. 460 to 463.* These views show clearly the insulated hangers and method of suspension. It will be observed that triple insulation

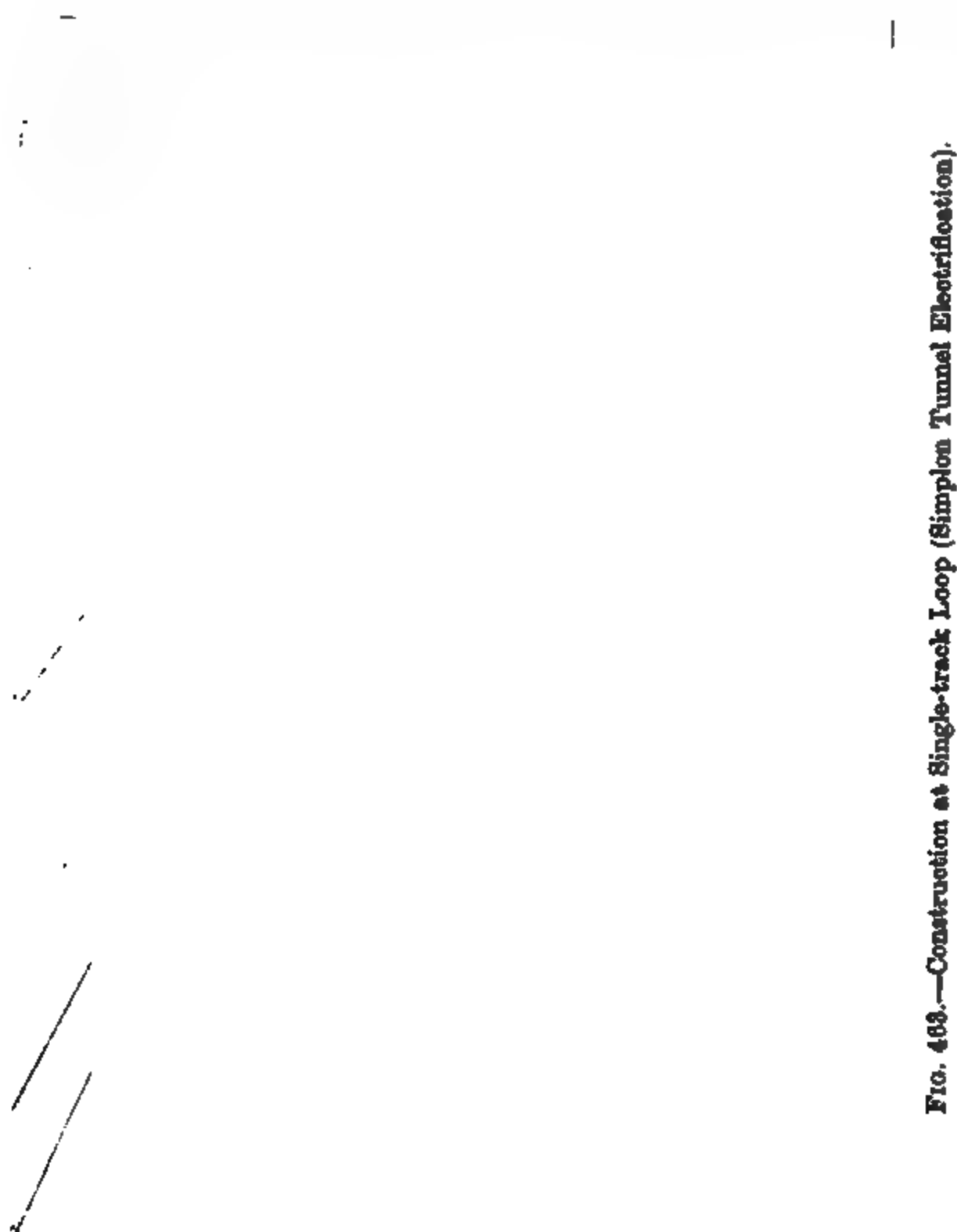
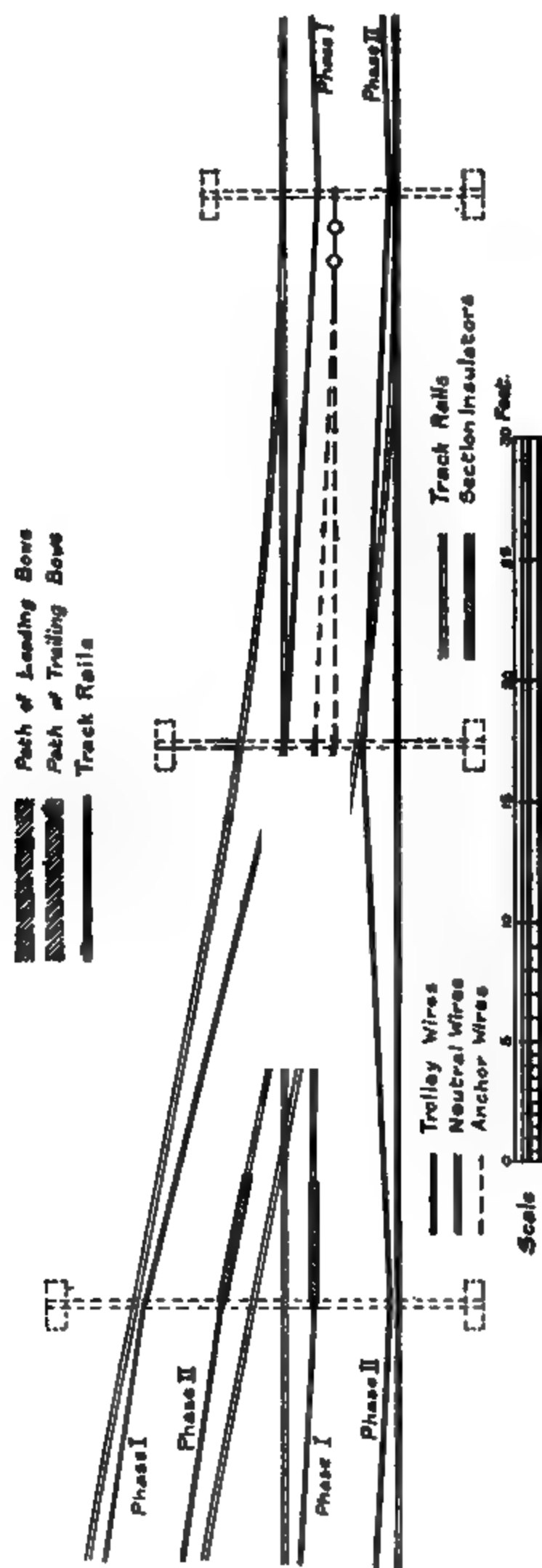


FIG. 463.—Construction at Single-track Loop (Simplon Tunnel Electrification).

is used throughout, and that two types of hangers are adopted on the Giovi lines, one being similar to that used on the Simplon line.

In the Simplon type of hanger the trolley-wire is supported by an insulated bolt, which is carried in a cross-bar fixed into hooded porcelain insulators. These insulators are fitted with metal caps, which are pro-

* The author is indebted to Mr. A. M. Willcox (Editor of the *Tramway and Railway World*) for the blocks of Figs. 460, 461, 462.



FIGS. 464a, 464b.—Method of Determining Position of Trolley-wires at Junctions on Three-phase Railways.

vided with clamping screws for attachment to the supporting span-wire. The hangers shown in Fig. 460 are provided with porcelain insulators of a uniform design, and the insulators for each hanger are fixed into a casting. Under normal conditions the two hangers are attached to the same span-wire, and are spaced 1 metre between centres, the span-wire being insulated from the bracket-arm by porcelain insulators of either the shackle or the spool type.

In three-phase railways the portions of the overhead work requiring the most care in design and erection are **cross-overs** and **junctions**. At these places it is necessary to provide a continuous path for each bow collector, and at the same time prevent a bow from being in contact with wires of opposite polarity. It will be apparent, therefore, that neutral sections and section-insulators are required in addition to live wires.

The positions of the live wires, dead sections, and section insulators can be determined by marking off, on a plan of the track rails, the space swept out by each bow.* If the areas so obtained are marked in a distinctive manner, then it is obvious that dead sections must be inserted where these areas overlap. This may be illustrated by considering the simplest case of a Y-junction on a single track. A plan is first made of the position of the track rails, and the space swept out by each bow is then obtained by the use of a template. The result of this process is represented in Fig. 464a. It will be apparent from this diagram that the outer wires may be continuous, but the inner wires must be fitted with section-insulators and a dead section where the tracks converge to a single road. The overhead wiring must therefore be arranged as indicated in Fig. 464b. The section insulators generally consist of treated wood, and have a length of about 3 ft.

OVERHEAD CONSTRUCTION AT LOW OVER-BRIDGES AND TUNNELS

The minimum height of the trolley-wire above the track rails is determined by the minimum clearance allowed above the "loading-gauge." †

Obviously, at very low bridges, which have been constructed with the minimum clearance, we shall not have space in which overhead wires and their supports can be erected. Therefore we must either lower the track to obtain the necessary space, or instal a dead-section, which consists of earthed guide-wires attached directly to brackets fixed to the bridge. In the latter case the trolley-wire is dead-ended at each end of the bridge, and a neutral (or insulated) section is inserted between the dead wires and the trolley-wires to provide a continuous path for the bow.

At bridges where the necessary space is available for the erection of overhead wires, the design of the supports for the insulators, &c., will be influenced largely by local conditions. In cases where the width of the bridge is not great, it is possible to arrange the framework carrying

* This may be done most conveniently by preparing a plan or template (on tracing paper) of the wheel-base of the locomotive or motor-coach with the position and width of each bow marked.

† The "loading-gauge" is defined as the profile within which every vertical section through the rolling stock must be contained. It varies slightly with different railways.

the insulators at each end, but in other cases it may be necessary to fix intermediate insulated supports under the bridge.

The arrangement of the overhead work at bridges on the **London, Brighton, and South Coast Railway Co.**'s single-phase system is illustrated in Fig. 465, and the method illustrated has been found to meet practically all cases on this railway. The illustrations show sufficient detail to render a detailed description unnecessary. It is interesting to note that the insulators are of the same type and size as those erected on the gantries (p. 549), the "catenary" insulator being used to insulate

FIG. 465.—Construction at Over-bridge and Tunnel (London, Brighton, and South Coast Railway).

the projecting U-shaped member (to which the catenary wires are clamped, from the framework, while the "gantry" insulator is used to insulate this framework from the bridge.

On the electrified lines of the **Midland Railway** (p. 551) the overhead wires had to be taken through several low bridges of the arch type. In this case the catenary wire was dead-ended at each end of the bridge, and the auxiliary and trolley wires were run through. At several of these arches over double track it was necessary to run the wires towards

the centre of the arch in order to obtain sufficient clearance and to keep the wires and insulators out of the direct blast from steam locomotives.

In all cases where live wires have to be taken under bridges, &c., it is necessary to arrange that the gradient between the two levels of the trolley-wire is such that the bow will remain in contact with the trolley-wire at all speeds, otherwise considerable flashing will occur. With the ordinary type of bow collector, a gradient of 1 in 50 is satis-

FIG. 466.—Construction at Hoosac Tunnel (Boston and Maine R.R.).

factory at speeds of 40 m.p.h., but at higher speeds and with a pantograph collector the gradient must be limited to about 1 in 100.

Tunnels.—An example of overhead construction (on the double catenary system) in a double-track tunnel on the suburban system of the **London, Brighton, and South Coast Railway** is given in Fig. 465. Here the "gantry" insulators are carried on joists, which are bolted to cast-iron side brackets built into the tunnel, the brackets and joists being covered with cement to prevent corrosion.

A further example, showing the application of the single catenary system to a double-track tunnel, is given in Fig. 466. This particular construction has been installed in the **Hoosac Tunnel** (on the Boston and Maine Railroad), which is 25,080 ft. (4.75 miles) long. Traffic is

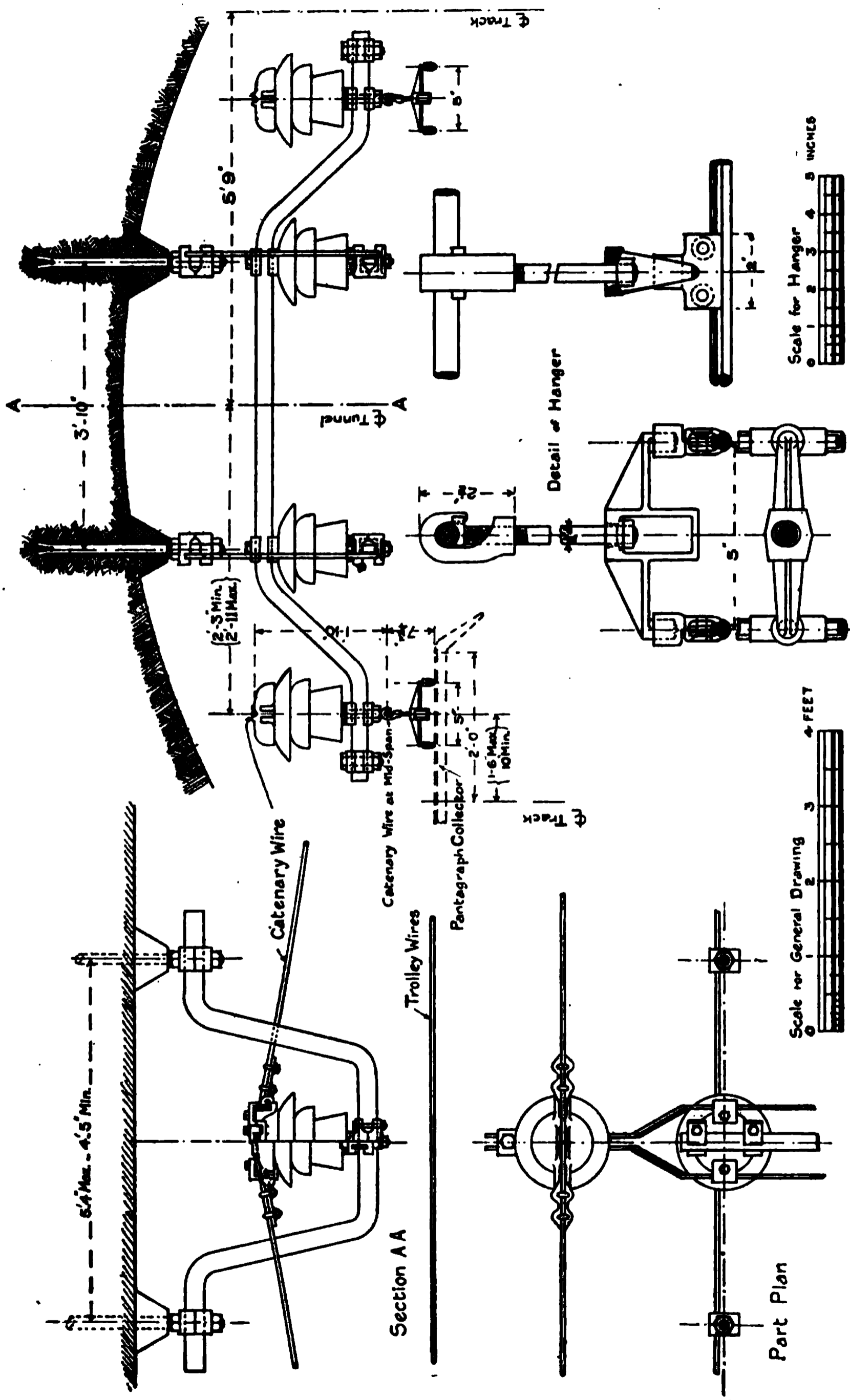


FIG. 467.—Details of Construction for Hoosac Tunnel.

handled by electric locomotives supplied with single-phase current at 11,000 volts. The electric locomotives are coupled to the steam locomotive, and haul the complete train through the tunnel.

The trolley-wires for each track consist of two 4/0 B. & S.G. grooved

FIG. 468.—Construction in Simplon Tunnel.

“phono-electric” * wires, suspended, in the same horizontal plane, from a stranded copper catenary wire ($\frac{1}{2}$ in. in diameter) by bronze hangers of the type shown in Fig. 467. By adopting a copper catenary wire (which is continuous throughout the tunnel) it has not been necessary to run feeders through the tunnel.

* See p. 508 for properties of this material.

The catenary wire is supported at intervals of about 100 ft. on triple petticoat porcelain insulators, the corresponding insulators for each track being fixed to a framework supported by a pair of similar insulators (see Fig. 466). The latter insulators are fixed to stirrups which are bolted to the crown of the tunnel. In order to obtain sufficient clearance, the catenary wires are placed 14 in. inside the centre of the track. Each insulator will withstand a dry test of 150,000 volts, and two insulators are in series between the trolley-wire and ground. This high factor of safety was considered desirable on account of the length of the tunnel and the large quantity of moisture present. As the insulators form the most important link in the overhead construction, it is good policy to adopt a high factor of safety, especially in a long tunnel. Moreover, it has been stated * that an insulator to withstand 150,000 volts only costs about four shillings more than one to withstand 40,000 volts.

It will now be interesting to compare the above examples of catenary construction with the direct system of suspension adopted in three-phase electrification. Examples of long tunnels electrified on the three-phase system are the Simplon (12.5 miles, single track) and the Mont Cenis (8.7 miles, double track).† In each case the operating voltage is about 3000 volts, and two trolley-wires are used in conjunction with the rails.

The method of construction in the **Simplon Tunnel** is comparatively simple, as will be seen from Fig. 468. The two twin-hangers (which are similar in general design to the hangers illustrated in Fig. 463, p. 562) are clamped to a span-wire which is suspended from shackle-type porcelain insulators, the latter being attached to eye-bolts fixed to plates in the tunnel wall. The span-wires are erected 80 ft. apart on straight track, and 40 ft. apart on curves.

Each twin-hanger supports two trolley-wires‡ (each 0.315 in. in diameter) which are connected in parallel. Since the temperature variation in the tunnel is small, the trolley-wires can be erected with sufficient tension to give only a small sag.

In the **Mont Cenis Tunnel** the twin trolley-wires are supported from hangers, of the same design as those illustrated in Fig. 460 (p. 560), and the latter are clamped to a span-wire which is suspended from insulators on a pipe framework fixed to the tunnel wall.

* *Transactions of the American Institute of Electrical Engineers*, vol. 30, p. 1437. Paper by Mr. W. S. Murray on "Trunk Line Electrification." Mr. Murray has informed the author that the cost of insulators for a given length of main-line construction (of the type illustrated in Fig. 453) is only 1.75 per cent. of the total costs of the overhead construction. It is, therefore, poor policy to attempt to cut down the size of the insulators on main-line electrifications.

■ In connection with the costs of overhead construction for main lines see a paper by Mr. E. J. Amberg on "Overhead Contact Systems—Construction and Costs" (*Proceedings of the American Institute of Electrical Engineers*, vol. 34, p. 1255).

† The Cascade Tunnel (2.7 miles long, single track) of the Great Northern Railway (U.S.A.) is also electrified on the three-phase system at 6600 volts.

‡ The object of adopting twin trolley-wires was due to the difficulty of handling a single wire of heavier cross-section. Further, if one wire should develop a defect, the service can be maintained by the other wire.

CHAPTER XXVI

FEEDING AND DISTRIBUTING SYSTEMS FOR TRAMWAYS AND RAILWAYS

WHEN electrical energy has to be supplied from a power station (or a sub-station) to a number of circuits at a constant voltage, the various circuits must be connected to distributing cables (called *distributors*), which are fed at suitable points (called *feeding points*) by other cables (called *feeders*). The latter cables connect the feeding points of the distributors to the station bus-bars, and their function is to maintain these points of the distributors at a definite voltage. The function of the distributors is to supply the various circuits at practically constant voltage. This difference in the functions of distributors and feeders has an important effect upon the considerations affecting the design of these cables.

Thus, in the design of a distributor, the principal consideration is the permissible variation of voltage, which, in lighting systems,* is subordinate to considerations of economy. On the other hand, a feeder may be designed for a voltage drop which will result in minimum operating expenses, the latter including not only the cost of the losses in the cable, but also the interest and depreciation charges thereon.

Now in electric traction systems the trolley-wires and the track rails (or the two sets of conductor rails) form the distributors, and it is apparent that, if a uniform voltage is required on the cars, these distributors must be fed through feeders. The feeding and distributing system, however, differs in many respects from that for electric lighting purposes. For instance, in the former case the load factor is much higher than that in the latter case, while the permissible variation of voltage is much greater, and is not restricted by Board of Trade regulations. But there are other important differences, of which the principal refers to the manner in which the loads are applied to the distributors. Thus, in a lighting system, the loads occur at definite points along the distributors, but in the traction system the loads are variable not only in magnitude, but also in position. Moreover, the traction distributing system must, in the case of tramways, conform to certain **Board of Trade regulations** (see pp. 633, 637), chief among which are the following :—

(1) The voltage on the trolley-wire shall not exceed 550 volts, while that at the generating station (or sub-station) shall not exceed 650 volts.

(2) The trolley-wire shall be divided into sections not exceeding one half-mile in length.

* The permissible variation of voltage in electric lighting distributors is fixed by the Board of Trade at 4 per cent. of the "declared voltage" of distribution.

(3) The potential difference between any two points of the (track) rail return system shall not exceed seven volts.

A consideration of these regulations will clearly show that, for overhead tramways, separate feeding systems will be required for the trolley-wire and the track rails; while, on account of the low voltage drop in the track rails, the variation of voltage at the cars will be principally dependent on the voltage drop in the trolley-wire. In any given case the permissible variation of voltage must obviously depend on service conditions, and the minimum voltage must be such that the schedule speed can be maintained under all conditions of traffic. In some cases a maximum voltage variation of 10 per cent. may be permissible, but in other cases—particularly in central districts with heavy traffic—a lower maximum variation will generally be desirable.

The calculation of the length of section corresponding to the maximum permissible voltage drop is not so straightforward as that in the case of a lighting system, since the loads are variable both in magnitude and position. Moreover, in practice, occasional blocks in the traffic will occur, with the result that the number of cars on one section may be much greater than that under normal conditions of traffic. Hence a certain amount of judgment must be exercised in deciding upon the length of sections, and each case must be considered separately. Of course, in railway service, where the trains run to a definite time-table, the average load on a section can be computed with a fair degree of accuracy when the speed-time and current-time curves are available, but in tramway service the variable traffic conditions do not warrant such an elaborate computation.

For normal traffic conditions the average voltage drop in any section of the trolley-wire may be obtained by considering the cars to be uniformly spaced throughout the section and each car to be taking the average current, which may be from 15 to 30 amperes, according to the type of car, the size of equipment, and the nature of the service.

In deciding upon the length of a distributing section of the trolley-wire, a value is fixed for the maximum voltage drop. The average voltage drop in the section is then assumed as a certain percentage of the maximum drop, and the length of the section is obtained from a knowledge of the car service and particulars of the trolley-wire. Thus, suppose we require the length of a section of 2/0 S.W.G. single trolley-wire on which a maximum voltage drop of 50 volts is permissible. The cars operate at a schedule speed of 8 ml.p.h., with an interval of $2\frac{1}{2}$ minutes between cars, and the average current per car may be assumed as 20 amperes.

From the given data we obtain the distance between consecutive cars as $\left(\frac{2.5}{\frac{1}{3} \times 60} = \right)$ one-third mile, and from Table XXVIII (p. 508) we obtain the resistance of 1 mile of 2/0 S.W.G. copper trolley-wire as 0.46 ohm.

Hence the resistance of trolley-wire between consecutive cars

$$= \frac{1}{3} \times 0.46 = 0.153 \text{ ohm.}$$

The average voltage drop may be assumed as 60 per cent. of the maximum drop, or $(0.6 \times 50 =)$ 30 volts.

The length of trolley-wire corresponding to this voltage drop is best determined by an indirect method as follows :—

Make a series of calculations of the voltage drop corresponding to a definite number of cars, with one car at the end of the section in each case. Thus, for a section of 1 mile long, we shall have one car at the end of the section, and two cars intermediate between the end and the feeding point. The average voltage drop will equal

$$(0.153 \times 20(3+2+1)=) 18.4 \text{ volts.}^*$$

Similarly, for sections $1\frac{1}{2}$ and $1\frac{3}{4}$ miles long, the average voltage drops will be respectively $(0.153 \times 20(4+3+2+1)=) 30.6$ volts and $(0.153 \times 20(5+4+3+2+1)=) 45.9$ volts.

Therefore the required length of the section of trolley-wire is $1\frac{1}{2}$ miles.

The Board of Trade regulations, however, require the trolley-wire to be divided into sections not exceeding one half-mile in length. Hence it may be desirable to increase slightly the voltage drop in order to avoid the sub-division of a half-mile section between two feeders.

Let us now consider the **design of feeders**. Obviously, if the voltage at the feeding points of the distributors is maintained constant, the voltage drop in the feeders will not affect the voltage variation in the distributors. Consequently the voltage drop in the feeders can be selected at a value which will result in the most economical operation.

Now, in a feeder of given length, carrying a given current, the voltage drop will vary inversely as the cross-section, or directly as the current density. Hence it is necessary to obtain the relation between the current density and the operating costs. The latter obviously comprise the cost of the energy lost in the feeder, and the interest and other charges on the capital expenditure. A portion of the capital expenditure, however, will be uninfluenced by the cross-sectional area of the cable, while the remainder will be directly dependent upon the cross-sectional area of the cable. For example, the costs of excavations, &c., laying of ducts and drawing-in will depend only on the length of cable and the number of cables being laid. Similarly, a portion of the cost of the insulation will be independent of the cross-section of the cable.

Therefore let the cost per mile of the cable, laid and jointed, be $(£)C=(A+Ba)$, where a denotes the cross-section of the cable, B the portion of the capital cost which is dependent on the cross-section,

* In a distributor fed from one end and loaded with a number of loads, the voltage drop is calculated as follows :—

Let I_1, I_2, I_3 , &c., denote the load currents in amperes ; $L_1, L_2, L_3 \dots$ denote the distances of the loads from the feeding points ; $l_2, l_3 \dots$ denote the distances between consecutive loads, l_2 representing the distance between the loads I_1 and I_2 , &c. Then, if r denotes the resistance of unit length of the distributor, the voltage drop (v) from the feeding point to the n th the load will be :

$$\begin{aligned} v &= r\{L_1(I_1 + I_2 + I_3 + \dots I_n) + l_2(I_2 + I_3 + \dots I_n) + l_3(I_3 + \dots I_n) + \dots l_n I_n\} \\ &= r(L_1 I_1 + L_2 I_2 + L_3 I_3 + \dots L_n I_n), \\ \text{since } L_2 &= L_1 + l_2 ; L_3 = L_1 + l_2 + l_3 ; \text{ \&c.} \end{aligned}$$

In the special case when the loads are all equal and occur at equal distances along the distributor, then we replace

$$I_1, I_2, I_3, \dots \text{ by } I, \text{ and } L_1, l_2, l_3 \dots \text{ by } l,$$

and obtain

$$v = r l I (n + (n-1) + (n-2) + \dots 1) = r l I \times \frac{1}{2} n(n-1)$$

in which n denotes the number of loads.

and A the remaining portion of the capital cost, which is independent of the cross-section.

The resistance of 1 mile of copper cable, 1 sq. in. in cross-section, may be taken as 0.0425 ohm. Hence the resistance of 1 mile of cable of cross-section = a sq. in. will be $0.0425/a$ ohm.

If I is the R.M.S. value of the current in amperes passing through this cable for a period of h hours per annum, then the cost $[(£)E]$ of the I^2R losses in the cable per annum will be given by

$$(\pounds)E = I^2 \times \frac{0.0425}{a} \times \frac{hp}{240 \times 1000},$$

where p is the price in pence of a Board of Trade unit (i.e. 1 kw-hour) delivered to the cable. (Generally p may be taken as the price of a unit at the switchboard.)

Also, if m is the percentage interest and depreciation charges on the capital cost of the completed cable, the annual charges will be

$$\frac{m}{100} \pounds(C) = \frac{m}{100} (A + Ba).$$

Therefore the annual cost of the cable will be

$$\frac{m}{100} \pounds(C) + \pounds(E) = \frac{m}{100} (A + Ba) + \frac{I^2 hp}{a} \times \frac{0.0425}{240,000},$$

which will be a minimum when $\frac{m}{100} Ba = \frac{I^2 hp}{a} \times \frac{0.0425}{240,000}$.

Whence
$$\frac{I^2}{a^2} = \frac{mB}{hp} \times 5.64 \times 10^4,$$

or $\frac{I}{a}$ (i.e. the current density) $= 237.5 \sqrt{\frac{mB}{hp}} \dots \dots \dots (57)$

Hence the **most economical current density** is that which makes the annual cost of the losses in the cable equal to the variable portion of the annual charges on the capital cost.* If this current density exceeds that corresponding to the limiting operating temperature of the cable, then obviously the cross-section must be chosen on the latter basis.

It is important to note that the voltage drop in the feeder does not appear in the above expression, although, when the current density is determined, the voltage drop is also indirectly determined.

Now cases will arise with long feeders where the voltage drop, corresponding to the most economical current density, will be excessive, and in these circumstances either the cross-section must be increased to give a lower voltage drop, or a booster must be used in conjunction with the cable. The booster, however, has losses and capital charges, which are additional to the operating costs of the cable. Whether or not it will be economical to adopt a larger cable, or to instal a booster in conjunction with the original cable, will depend on the total annual costs in the two cases.

In obtaining the **total annual costs for a "boosted" cable**, the losses in the booster may be allowed for by increasing the cost per kw-hour delivered to the cable, while the annual charges on the booster may be added to the annual charges on the cable. But the increase in

* This relation is usually known as Kelvin's law.

the cost of energy delivered to the cable, combined with the additional annual charges on the booster set, must be allowed for in determining the most economical current density. Consequently the above equation must be modified as follows :—

If p denotes the cost (in pence) of 1 kw-hour at the switchboard, and η is the efficiency of the booster set at the average working load, then each kw-hour of boosted energy delivered to the cable will cost p/η on account of the losses in the booster set. Again, if (£) X denotes the capital cost of the booster set per kw output, n denotes the percentage interest and depreciation charges per annum, and (£) Y denotes the cost of attendance and maintenance per kw output per annum, then the charges on the booster set per kw output per annum will be $240 \left(\frac{nX}{100} + Y \right)$ pence. Hence, if the booster is in service h hours per annum, the charges per kw-hour will be $\left(\frac{0.01nX + Y}{h} \right) 240$ pence, and the total cost of 1 kw-

hour delivered to the cable will be $\left\{ \frac{p}{\eta} + \left(\frac{0.01nX + Y}{h} \right) 240 \right\}$ pence.

Therefore, the annual cost of the boosted cable (of cross-section a' sq. in.) will be

$$\frac{m}{100}(A + Ba') + \frac{I^2 h}{a'} \times \frac{0.0425}{240,000} \times \left\{ \frac{p}{\eta} + \left(\frac{0.01nX + Y}{h} \right) 240 \right\}.$$

Whence, the most economical current density $\left(\frac{I}{a'} \right)$ is given by

$$\frac{I}{a'} = 237.5 \sqrt{\frac{mB}{h \left\{ \frac{p}{\eta} + 240 \left(\frac{0.01nX + Y}{h} \right) \right\}}} \quad \dots \quad (58)$$

Examples.—Let us apply these equations to the determination of the most economical cross-sectional area for a feeder to supply a section of trolley-wire for tramway purposes.

Consider first an unboosted feeder, 1 mile long. The R.M.S. value of the current in the cable is 150 amperes, and the cable is in service 15 hours per diem. The variable component of the cost of the completed (paper insulated) cable may be taken at £140 per ton of copper. The interest and depreciation charges on the cable are 7 per cent., while the cost of 1 kw-hour delivered to the cable is 0.6 pence.

Now the weight of copper in a cable 1 mile long and 1 sq. in. in cross-section is 9.1 tons, and therefore the term B in the above equation becomes $9.1 \times 140 = 1275$. Hence, substituting in equation (57), we obtain the most economical current density as

$$\frac{I}{a} = 237.5 \sqrt{\frac{7 \times 1275}{15 \times 365 \times 0.6}} = 391 \text{ amperes per sq. in.}$$

The cross-section of the cable corresponding to this current density is $\left(\frac{150}{391} \right)^2 0.383$ sq. in., so that it will be necessary to use a 0.4 sq. in. cable.

A reference to the *I.E.E. Wiring Rules* * will show that a paper-insulated cable of this cross-section will carry continuously a current of 464 amperes.

The voltage drop in the feeder, corresponding to the R.M.S. current, will be

$$150 \times 1 \times \frac{0.0425}{0.4} = 16 \text{ volts.}$$

[NOTE.—0.0425 is the resistance (in ohms) of a cable 1 mile long and 1 sq. in. in cross-section.]

Consider now that the length of the feeder is increased to 2 miles, the other conditions remaining constant. A preliminary calculation will show that the voltage drop in the feeder, corresponding to the R.M.S. current of 150 amperes, is 47.2 volts, so that it will be necessary to use a booster with the feeder. The capital cost of the booster set (including switchgear) may be assumed as £15 per kw output, on which the interest and depreciation charges are 12 per cent. per annum. The cost of attendance and maintenance may be assumed as £0.4 per kw output per annum.

Hence, assuming the efficiency of the booster set (at the average working load) to be 75 per cent., and substituting in equation (58), we obtain the most economical current density for this boosted feeder as

$$\begin{aligned} \frac{I}{a'} &= 237.5 \sqrt{\frac{7 \times 2 \times 9.1 \times 140}{15 \times 365 \left\{ \frac{0.6}{0.75} + 240 \left(\frac{0.01 \times 12 \times 15 + 0.4}{15 \times 365} \right) \right\}}} \\ &= 237.5 \sqrt{\frac{7 \times 2 \times 9.1 \times 140}{15 \times 365 \times 0.896}} \\ &= 363 \text{ amperes per sq. in.} \end{aligned}$$

The size of the cable is $\left(\frac{150}{363} \right)^2 0.412$ sq. in., say 0.4 sq. in.

The voltage drop in the feeder corresponding to the R.M.S. current of 150 amperes will be

$$150 \times 2 \times \frac{0.0425}{0.4} = 32 \text{ volts.}$$

If the maximum current is assumed to be $(2.5 \times \text{R.M.S. current})$, the voltage drop corresponding to the maximum current of 375 amperes in the feeder will be $(32 \times 2.5 =) 80$ volts.

If we assume the bus-bar voltage to be 25 volts higher than the voltage at the feeding points, then the maximum voltage required from the booster will be $(80 - 25 =) 55$ volts, and the maximum rating of the

booster will be $\left(\frac{55 \times 375}{1000} = \right) 20.6$ kw.

The booster will consist of a self-excited series generator designed with a "straight line" characteristic, and will be direct-coupled to a shunt motor. The booster will, of course, be connected between the positive bus-bar and the feeder.

It is apparent from these examples that an extensive tramway

* Issued by the Institution of Electrical Engineers. See also the *Journal of the Institution*, vol. 47, p. 829.

system, with heavy traffic, will require a number of boosted feeders for the positive distributing system when the supply is given from a central power station. In many cases it may not be possible to supply the system economically in this manner, and in these cases the low-tension distributing system must be supplied from a number of sub-stations, which may be located in the immediate neighbourhood of the distributing sections, so that only short feeders are required. The sub-stations are supplied with power from the generating station, and since a high voltage of transmission is essential for economical reasons, the sub-stations must contain converting machinery for supplying the tramway system at suitable voltage. The influence of sub-stations on the feeding system is discussed later in this chapter, while the equipment of sub-stations is discussed in the following chapter.

POSITIVE FEEDING AND DISTRIBUTING SYSTEMS FOR TRAMWAYS

The method of feeding the distributing sections of the trolley-wire will be influenced largely by traffic and economical considerations.* In districts with very heavy traffic, the traffic considerations will usually preponderate, and the feeding system must be arranged so that the opening of a feeder circuit-breaker at the generating or sub-station will only affect a small portion of the traffic. Under these circumstances it is desirable to provide a separate feeder for each half-mile section of the trolley-wire.†

In cases of extremely heavy traffic it may be necessary to increase the conductivity of the half-mile sections of the trolley-wire by continuing the feeder, or another auxiliary feeder (which may consist of an additional trolley-wire), along the section and tapping the trolley-wires to the auxiliary feeder at frequent intervals. With the conduit system, however, the relatively large cross-section of the conductor rails will provide sufficient current-carrying capacity for the heaviest conditions of tramway traffic, and auxiliary feeders are therefore unnecessary.

In systems with light traffic, considerations of economy become of greater importance, and consequently it is desirable to supply several half-mile sections of the trolley-wire from a single feeder. The two general methods of accomplishing this are shown diagrammatically in Figs. 469, 470. In these diagrams the section-insulators in the trolley-wire are indicated, as well as the "section" and "feeder-pillars," ‡ which contain the switches for isolating the sections of the trolley-wire in accordance with the Board of Trade regulations.

In Fig. 469 the trolley-wire is used as a distributor, each distributing section comprising two or more half-mile sections. The length of the distributing section is limited by the permissible voltage drop, as shown by the example on p. 572.

* For detailed examples of the design of the feeding and distributing system see a paper by Mr. Henry M. Sayers on "The Calculation of Distributing Systems for Electric Traction under British Conditions" (*Journal of the Institution of Electrical Engineers*, vol. 29, p. 692).

† The feeders for the half-mile sections must, obviously, be supplied from sub-stations.

‡ Feeder and section pillars are discussed later (p. 580).

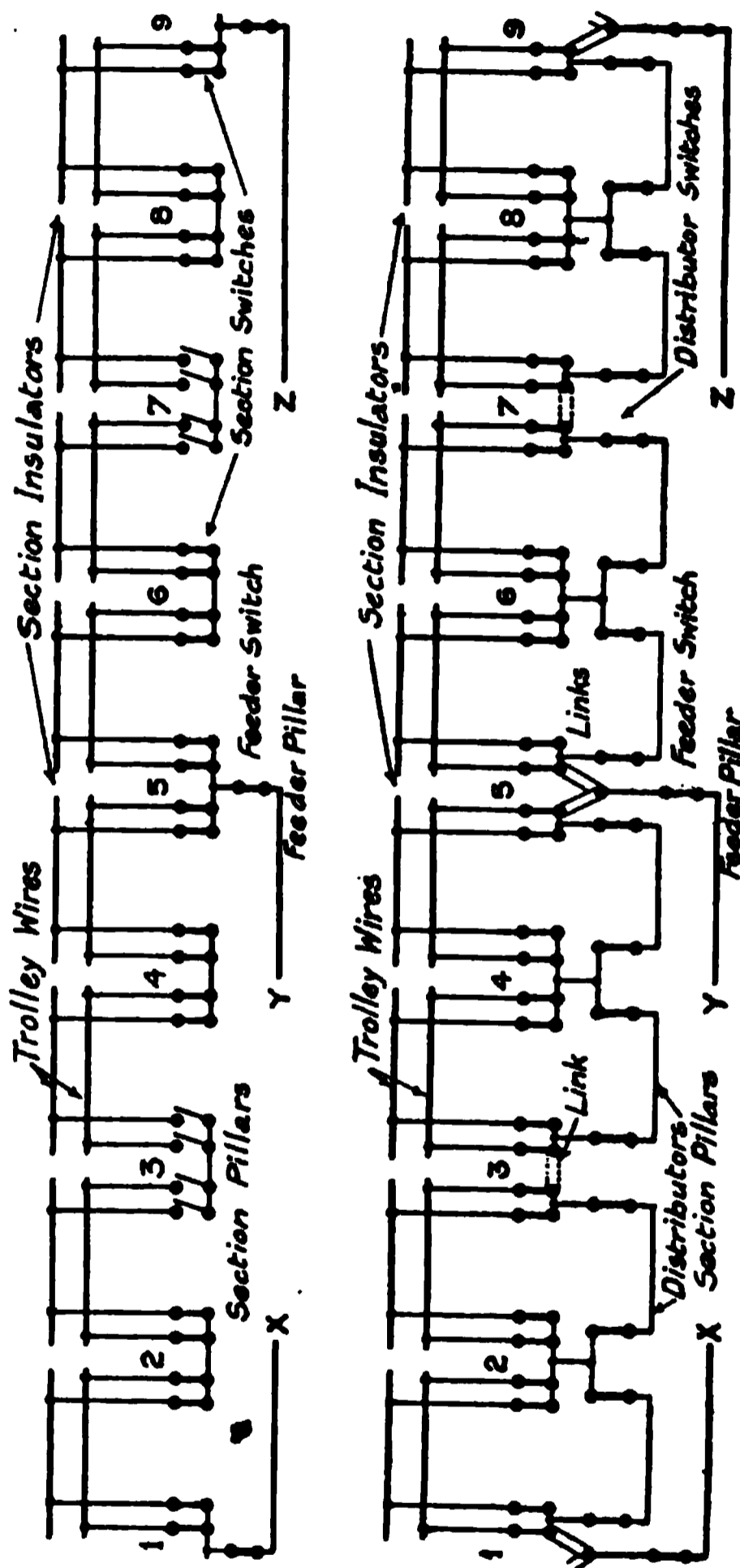
The alternative method to Fig. 469 is shown in Fig. 470. In this method—which permits the use of a smaller number of feeders than the preceding method—feeders of large cross-section are run to a few points in the system, from which the current is distributed to the various half-mile sections of the trolley-wire by means of graded distributing cables.

A comparison of these methods will show that the method with graded distributors (Fig. 470) is more economical in copper than the method of Fig. 469, since it permits of the adoption of long distributing sections. Moreover, with this method the variation of voltage between adjacent sections of the trolley-wire will be smaller than that for the method of Fig. 469. On the other hand, in the event of the feeder circuit-breaker opening, or a breakdown of the feeder occurring, the method of Fig. 470 results in a greater temporary interruption of traffic than the method of Fig. 469. But in the case of a breakdown of the feeder, the supply can be maintained to either side of the feeding point through the distributors connected to the adjacent feeders, although this may result in the overloading of some of the distributors.

It may be of interest to compare the methods of maintaining the continuity of the service—due to, say, a breakdown of a feeder—in the two cases. For instance, suppose a fault occurred on feeder Y. With the system of Fig. 469, feeder pillar No. 5 would be visited first, and the feeder switch opened.

Section pillars Nos. 3 and 7 would then be visited, and the section switches in these pillars would be closed, thereby dividing the load of feeder Y between feeders X and Z. In some cases it may be desirable to open the section-switches in pillar No. 5.

With the system of Fig. 470, feeder pillar No. 5 would be visited first, and the links interconnecting the distributor and feeder switches would be removed. Feeder pillars Nos. 3 and 7 would then be visited, and the distributor switches would be connected together by a link, as



Figs. 469, 470.—Methods of Feeding and Sectionalising Trolley-wires for Tramways.

indicated in Fig. 470. One half of the section normally supplied from feeder *Y* is then transferred to feeder *X*, while the other half of the section is transferred to feeder *Z*.

NEGATIVE FEEDING AND DISTRIBUTING SYSTEMS FOR TRAMWAYS

The exact calculation of the voltage drop in the track rails is considerably more complicated than that for the trolley-wire on account of leakage currents due to the rails being uninsulated. For instance, a portion of the return current may reach the generating or sub-station *via* the earth, while the earth may also act as a diverter (or shunt) to the track rails, thereby relieving the rails of some of the return current. Although it is possible to calculate the voltage drop in the track rails under the latter conditions,* it is preferable to neglect the effect of the conductivity of the earth, and to design the distributing sections so that the voltage drop under the worst conditions does not exceed the Board of Trade limit of 7 volts.

If the current in the rails is due to a number of cars, equally spaced along the track, the voltage drop in a length of the track rails can be calculated by a method similar to that adopted for the trolley-wire. In determining the resistance of the rails, the resistance of the bonded, or welded, joints must be included (see p. 490); while, if the cross-bonding occurs at frequent intervals, the individual track rails may be considered as being permanently connected in parallel. Thus, from the data in Chapter XXII, the resistance of 1 mile of B.S.S. No. 4 tramway rail (including resistance of bonded joints) is 0.047 ohm, and therefore the resistance of 1 mile of double track may be considered to be 0.012 ohm.

In deciding upon a value for the permissible voltage drop in the rails, the possible future developments of the tramway system should be considered, as well as the effects of blocks in the traffic, and "bunching" of the cars at certain parts of the system. The average voltage drop under normal conditions should therefore be assumed at a value not in excess of 5.0 volts.

With the voltage drop given, and the resistance of the track known, the length of the rail distributing sections can be determined from a knowledge of the electric loading. In many cases it is convenient to consider that the loading is uniformly distributed throughout the distributing section (*i.e.* the current decreases uniformly from the feeding point), so that the voltage drop along the section follows a parabolic law.†

The length of a distributing section corresponding to a definite voltage drop is then readily determined, and the position of the feeders naturally follows. Since the rails are continuous throughout the system, the curve of voltage drop between adjacent feeding points will be a para-

* See *The Electrician*, vol. 45, p. 595.

† If i is the rate of increase of the current along the rail from the dividing point (where the current is zero) and r is the resistance of unit length of the rail, then the current at any point, distant x from the dividing point, will be ix , and the voltage drop in an element of rail length dx will be $ix r dx$. Hence the voltage drop (v) in a length L from the dividing point will be given by

$$v = \int_0^L ix r dx = ir \left[\frac{x^2}{2} \right]_0^L = \frac{i r L^2}{2}.$$

Thus v is proportional to L^2 , and the curve connecting v and L is a parabola.

bola with the zero points at the feeding points. This is illustrated by the diagram of Fig. 471, in which the straight lines $o c o' c o''$ represent the distribution of current along the rail, and the parabolas $v x v_1 y v_2$ represent the variation of the voltage drop, the feeding points x, y being at the same potential.

Now the feeders connect the points x, y of the rails to the negative bus-bar, and it is apparent that with *uniform electric loading* of the rail sections, the feeders must be *designed for the same voltage drop*. Hence,

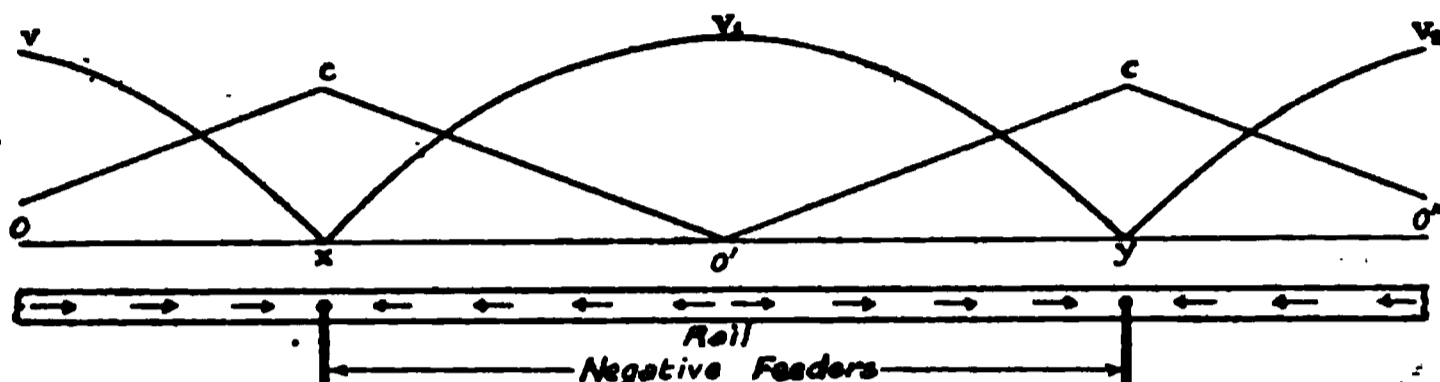


FIG. 471.—Variation of Voltage along Rail with Uniform Current-loading.

when long and short feeders are in use on the same system, it will be necessary either to connect resistances in series with the short feeders, or to neutralise a portion of the voltage drop in the long feeders by the use of boosters.*

Of these methods, the more economical one to adopt in a given case will depend on the relative values of the operating costs with resistances and with boosters.† It should be noted, however, that the voltage drop in the feeders and resistances affects the voltage variation at the cars and must, therefore, be taken into account. On the other hand,

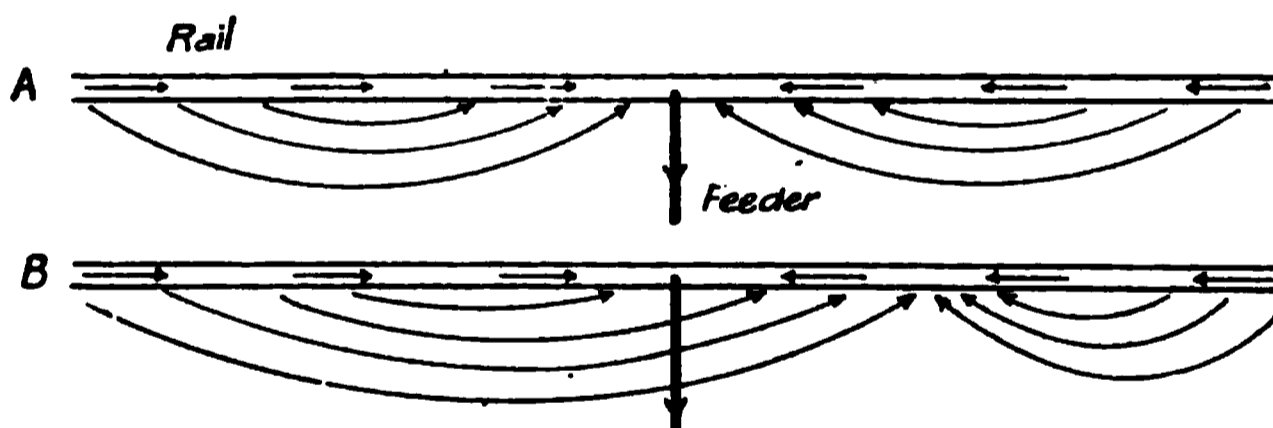


FIG. 472.—Distribution of Leakage Currents. *A*, equally loaded rail sections; *B*, unequally loaded rail sections.

with boosted feeders, the resultant voltage drop between rails and the negative bus-bar may be adjusted (within limits) to any value desired—including zero.

When boosted and unboosted feeders are adopted, and it is desired to maintain a uniform distribution of current in the rails, the resultant voltage drop in the boosted feeders must equal the voltage drop in the unboosted feeders. These are the ideal conditions for negative feeding systems and are represented diagrammatically in Fig. 471. In this case, the voltage drop along each distributing section of the rails is the same

* Boosters used in this manner (with negative feeders) are called *negative boosters*.

† In this connection see *The Electrician*, vol. 73, p. 607, where comparative costs have been calculated for the two cases by Mr. H. M. Sayers.

throughout the system, and, consequently, there is no tendency for leakage currents to pass between the sections. If the conductivity of the earth be assumed as uniform throughout the sections, the distribution of the leakage currents are as indicated in Fig. 472, *A*. On the other hand, if two adjacent sections are unequally loaded so that the voltage drops are unequal, there is an interchange of leakage current between the sections as indicated in Fig. 472, *B*. In order to prevent the interchange of leakage current between adjacent sections which are unequally loaded, the voltage drops in the sections must be equalised by adjusting the lengths of the sections in the ratio of the square-roots of the loading. Thus, if I_1 , I_2 denote the intensity of the loading (am-

peres per mile) of the respective sections of lengths L_1 , L_2 , then $\frac{L_1}{L_2} = \sqrt{\frac{I_1}{I_2}}$.*

It is apparent that with a large tramway system, supplied direct from a central power station, boosters will be required for the negative feeding system as well as for the positive feeding system.

Although the boosters for the positive and negative feeders are series machines, with similar characteristics, the method of operating them is different. Thus, the positive boosters are operated self-excited, but the negative boosters are separately excited; the armature being connected in series with the negative feeder, and the field winding being connected in series with the positive feeder supplying the corresponding sections of the trolley wire. The "boost" on the feeder is adjusted by means of a diverter rheostat connected in parallel with the field winding.

FEEDER AND SECTION PILLARS FOR TRAMWAYS

(1) **Overhead Tramways.**—The sectionalising of the distributing system is carried out by means of switches located in feeder and section pillars, which are placed in convenient positions adjacent to the track.

With the ordinary type of section insulator (Fig. 431, p. 519), a section pillar is required at every half-mile of the route, the pillar containing the switches for disconnecting the sections of the trolley-wire from one another and from the feeder or distributor. Illustrations of a **typical section pillar** are given in Fig. 473. The pillar consists of a cast-iron box structure with two doors, and is equipped with a marble (or slate) panel on which the switches and auxiliary apparatus are mounted. In the pillar shown in Fig. 473 (which is suitable for the intermediate section pillars in the method of distribution shown in Fig. 470), the four switches on the upper portion of the panel control the adjacent sections of the trolley-wire for the "up" and "down" tracks, while the two lower switches control the distributors which supply these sections. The two sets of switches are connected through a choking coil (as shown in the view of the back of the panel), while the trolley switches are also connected to a lightning arrester, which can be seen on the right-hand side of the back of the panel. Thus, any lightning discharges striking the trolley-wires are prevented from reaching the distributors. The front of the panel is arranged for a telephone set by means of which the motor-men and linesmen may communicate with the supply station.

* See *Journal of the Institution of Electrical Engineers*, vol. 50, p. 704. Paper by Messrs. J. G. and R. G. Cunliffe on "Some Problems in Traction Development."

FIG. 473 --Front and Back Views of Section Pillar (British Insulated and Helsby Cables).

FIG. 473a. --Section and Feeder Pillar (Brecknell, Munro, & Rogers).

Fig. 473a illustrates a pillar suitable for the feeder pillars (Nos. 1, 5, 9) in the method of distribution shown in Fig. 470. The four upper switches control the trolley-wire sections, as above, while the three lower switches control the feeder and distributors.

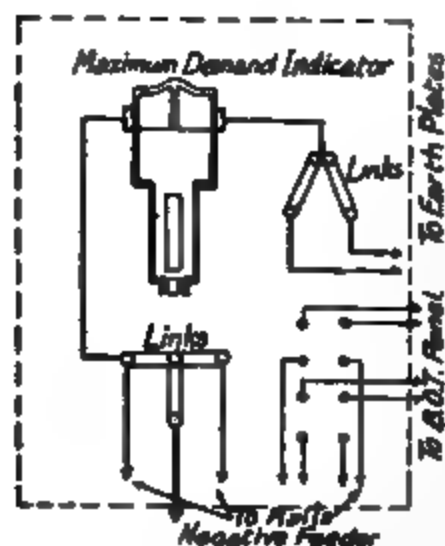


FIG. 474.—Arrangement of Negative Feeder Pillar.

On some systems feeder pillars are provided for the negative feeders. The arrangement of a **typical negative feeder pillar** is indicated diagrammatically in Fig. 474. In this case the negative feeder is connected to the track rails through a removable link. The potential leads from the rails are connected to a set of terminals, which may be connected by suitable links to pilot wires running from the feeder pillar to the Board of Trade panel (see p. 616) at the generating or sub-station. The station ends of the pilot wires are connected to recording voltmeters, which record the potential difference between

the various points of the rails in accordance with the Board of Trade regulations (see regulation 7, p. 635). The pillar is also equipped with

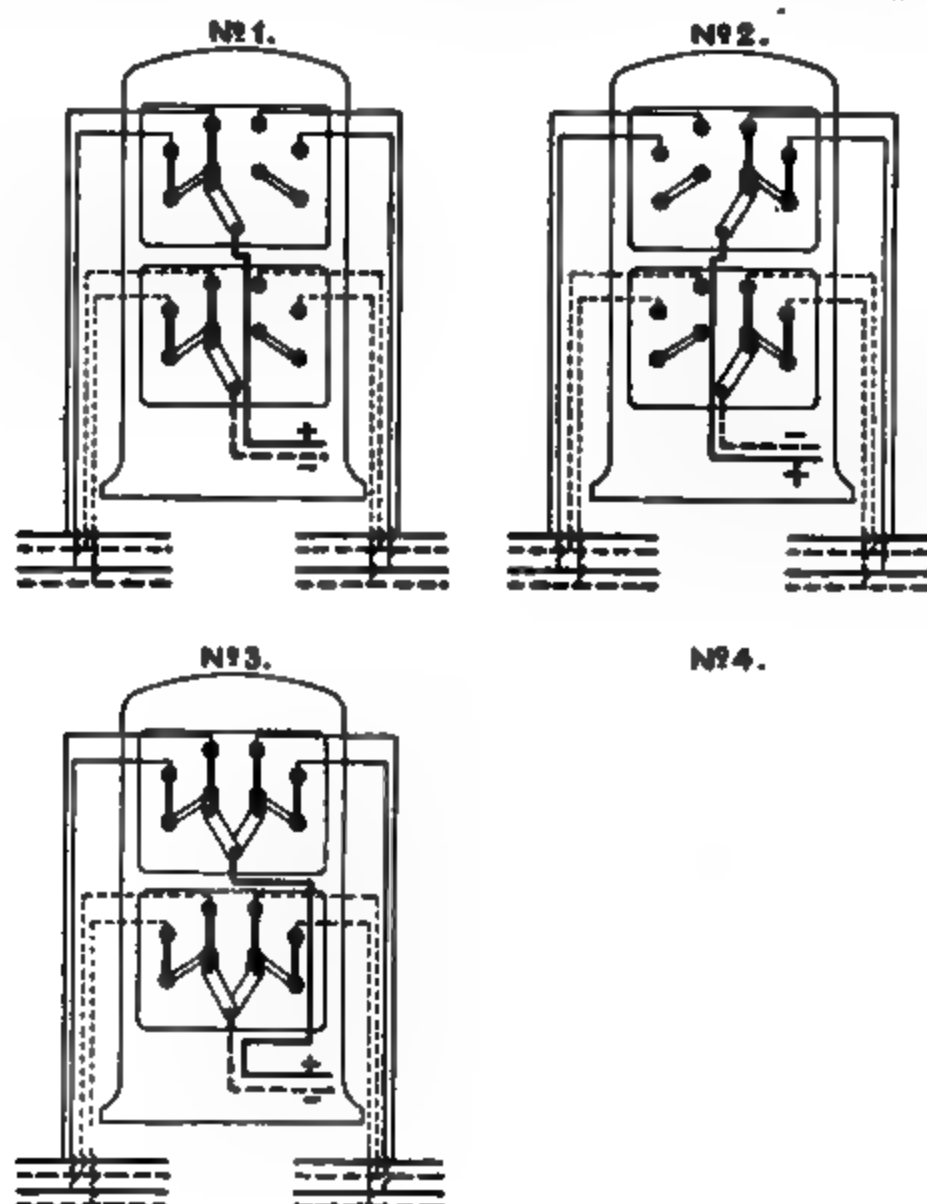


FIG. 475.—Arrangement of Switches in Feeder Pillars for Conduit Tramways.

a maximum demand indicator, which is connected between the negative feeder and the earth plates. This maximum demand indicator enables a record to be obtained of the maximum current returning to the station *via* the earth plates (see regulation 5f, p. 634).

(2) **Conduit Tramways.**—The feeder pillars for conduit tramways must be arranged with switches for controlling the positive and negative conductor rails. Diagrams showing the arrangement of the standard feeder pillar adopted for the conduit lines of the London County Council tramways are given in Fig. 475. The pillar is equipped with two panels, and on each panel are mounted four single-pole switches. The switches on the upper panel control, normally, the positive conductor rails. Each feeder terminates in a stud which may be connected to the switches on the respective panels by means of links at the back of the panels. In this manner several combinations between the feeders and the conductor rails can be made. Thus, in diagram No. 1, the feeders are connected to the left-hand switches, while in diagram No. 2 the feeders are connected to the right-hand switches. Again, in diagram No. 3, the links are arranged so that both of the adjacent sections of the track are fed from one feeder, while in diagram No. 4, the feeder is disconnected from the switches, and the right- and left-hand switches are connected together, so that one section of the conductor rails is fed from an adjacent section.

In the event of a fault occurring on the positive conductor rail of one section and the negative conductor rail of another section, it is necessary to transfer the positive fault to the negative side of the system in order that the service may be continued. The feeders are arranged so that their polarity may be reversed when required, this operation being carried out by means of reversing switches on the sub-station switch boards (see Chapter XXVII, p. 617, for details).

FEEDING AND DISTRIBUTING SYSTEMS FOR CONTINUOUS-CURRENT RAILWAYS

The design of the feeding and distributing system for urban and suburban railways, operating at an average voltage of 600 volts, is closely connected with the location of the sub-stations. The distance between the sub-stations is generally determined from considerations of the permissible variation of voltage at the trains, but it is advisable to consider also the location which will result in the minimum annual cost. In considering the voltage drop permissible on the conductor rails, the possibilities of delays due to signal stops should be taken into account, as well as the maximum service which is likely to occur on the different sections. Moreover, when operating with the maximum service, the headway between consecutive trains will be smaller than that under normal service conditions, and consequently the checks at signals will probably be increased. For this reason, it is important to consider the position of the signals (especially the "stop" signals) and the "block" sections in arranging the positions of the feeding points.

Since the trains operate to a definite time-table, which is closely adhered to under normal conditions, the demands on the sub-stations (under normal conditions of traffic) can be estimated with a fair degree of accuracy when the distance-time and current-time curves of the trains are available.

The number of trains on a given section of the track is best determined

from a **graphic time-table**, which is really a distance-time chart for each individual train. By means of this chart the positions of trains at important junctions—where two trains may have to use the same cross-over—can readily be seen. As a first approximation in the preparation of such a chart from a completed time-table, the distance-time curves of the trains may be assumed as straight lines. When the time-table is not available, the chart must be prepared from the running curves of the trains. If the positions of stations and the “stop” signals are indicated on the chart, an approximate idea of the maximum load of the section can be obtained.

Hence, when the voltage drop is fixed, and the resistance of the conductor rails is known, the maximum length of section—which can be supplied from a given feeder—can readily be determined. The position of the sub-station is then chosen to give the most economical arrangement of the feeders. In some cases, however, the sub-stations must be located at the passenger stations, and in these cases the possible positions of the sub-stations are fixed, and the feeding system must be designed accordingly.

As an **example of the method of determining the distance between the sub-stations** for a given case, we will assume that a service of 175-ton motor-coach trains has to be run over a double-track railway, on which the distance between the stations is 2560 feet; the schedule speed being 16 ml.p.h., and the duration of stop being 20 seconds. The track may be assumed to be straight and level. The trains are equipped with continuous-current motors, and the equipments are assumed to be identical with those of the 175-ton six-coach train for which the speed-time curve and energy consumption were calculated in Chapter XIX.

The average voltage on the trains is to be 600 volts, and the converting machinery, to be used in the sub-stations, is designed to give 600 volts at no load and 630 volts at full load. The distributing system consists of two (positive and negative) conductor rails weighing 100 lb. per yard.

The maximum service on the railway is 45 trains per hour in each direction.*

From Chapter XXIII we obtain the resistance of one mile of conductor rail (allowing for bonding) as 0·034 ohm, so that the resistance of the conductor-rail distributors per mile of the track will be 0·068 ohm.

Now the maximum voltage drop in the conductor rails, under the conditions of maximum traffic, should not exceed 40 volts, and as the starting current of a train is 1800 amperes, it is apparent that the maximum voltage drop will be obtained with this current flowing in a section 1725 ft. long. [The voltage drop in a mile of distributor, carrying a current of 1800 amperes, is $(0·068 \times 1800 =) 122·5$ volts, so that the

voltage drop in a length of 1725 ft. will be $\left(122·5 \times \frac{1725}{5280} =\right) 40$ volts.]

With a service of 45 trains per hour, the headway between trains is $\left(\frac{3600}{45} =\right) 80$ seconds; and since the running time is 89 seconds (see

* This is equivalent to the maximum service run over a portion of the District Railway, London. Obviously, this service is only possible in conjunction with automatic signalling.

page 431), a series of distance-time curves for consecutive trains can readily be constructed from the data given in Chapter XIX (p. 430). (A number of these curves for one track are given in Fig. 476.) On the same curve sheet, and on the time base, are plotted curves of the

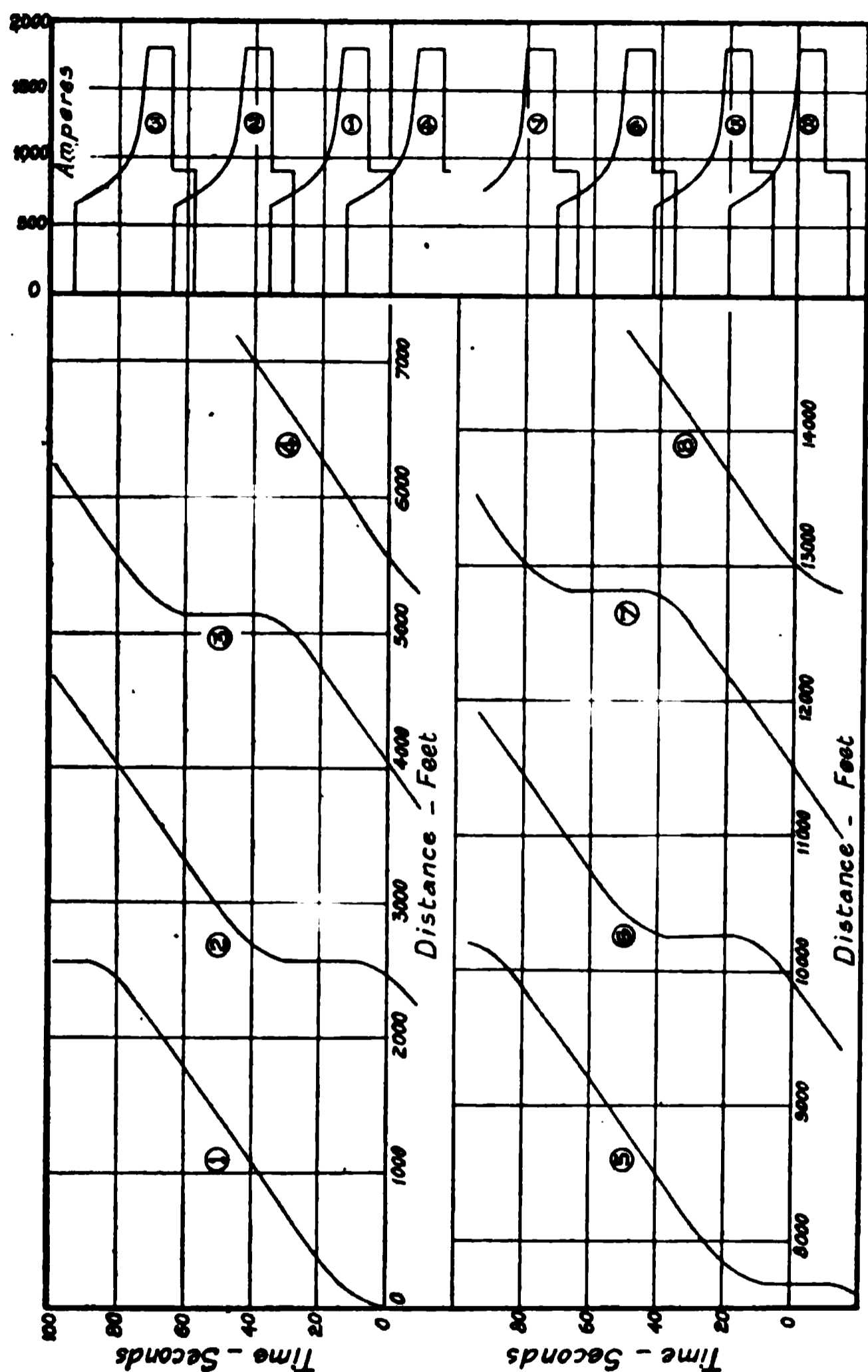


FIG. 476.—Method of Determining Distance between Trains taking Maximum Current.

current taken by a single train when operating to the above schedule (see Fig. 476).

We have now a chart from which the distribution of current in the conductor rails can be determined, and the problem is to ascertain the distance between the trains which are taking the maximum current (1800 amperes) at the same instant. Since the times of departure of the trains from consecutive stations are not identical, it will be necessary to

consider a fairly long length of track (about 3 miles) in order to obtain a number of trains starting at the same time. If a group of consecutive stations be designated A, B, C, D, &c., then we find that at a given instant trains are starting simultaneously from stations A, D, G. (There is, however, a short time interval of seven seconds between the successive starts.) We also find that when a train is starting from station B, other trains are starting from stations E and F. Thus, the maximum currents may be considered to occur simultaneously at stations 7680 feet apart.

The positions of the sub-stations can now be fixed when the system of feeding has been decided. In order to simplify matters we will assume

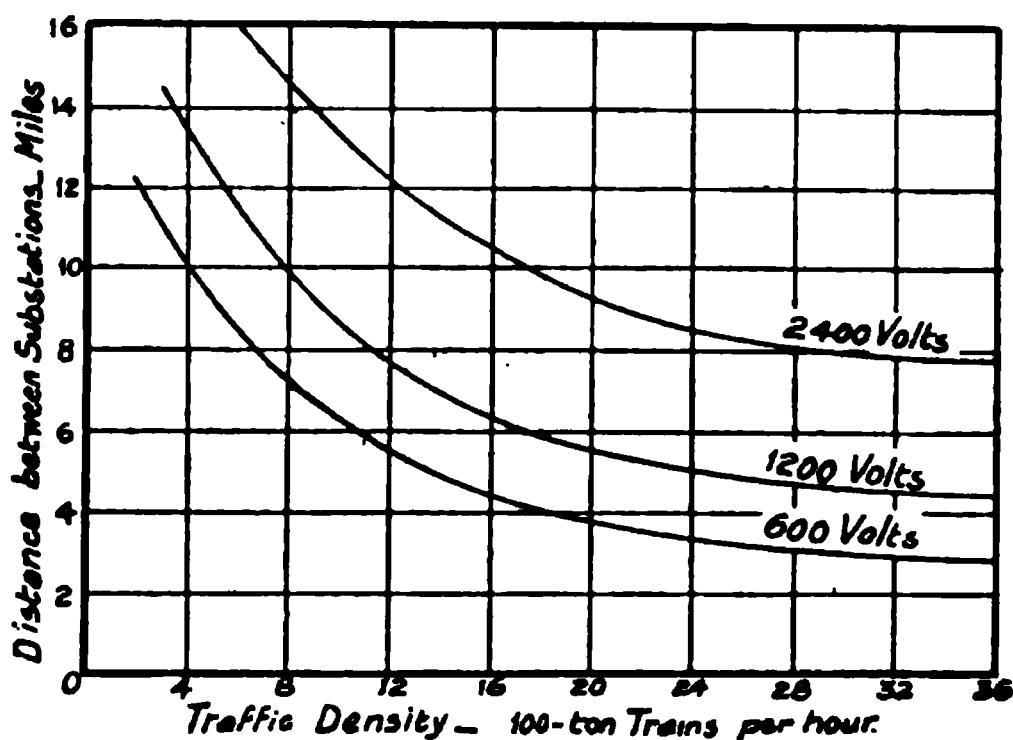


FIG. 477.—Most Economical Spacing of Sub-stations for 100-ton Trains operating on Suburban Service.

that the conductor rails are continuous between the sub-stations and that no intermediate feeders are adopted. Therefore, the feeding points in the conductor rails are opposite the sub-stations. A little consideration will show that if the sub-stations are located at the passenger stations A, D, G, &c., the maximum voltage drop will occur at the intermediate stations B, C, E, F, &c., and will equal 39.2 volts.* Thus, with this arrangement of the feeders and conductor rails, the sub-stations are 7680 feet (nearly 1.5 miles)

apart. Of course, if the conductor rails were also fed at intermediate points, the distance between the sub-stations would be increased; but in this case very heavy feeders would be required, due to the relatively high conductivity of the conductor rail (which is equivalent to that of a feeder 1.33 sq. in. in cross-section). Moreover, the intermediate feeders would probably require boosters in order to make them thoroughly effective.

Assuming that an "up" and a "down" train start together, the maximum load on a single sub-station will be $(2 \times 1800 \times 630 =) 2270$ kw. This figure does not allow for the additional loads occasioned by signal checks.

In the above example the positions of the sub-stations have been fixed from considerations of the permissible voltage variation at the trains. With systems on which the traffic consists of only a few trains per hour, it would be more economical to increase the distance between the sub-stations and adopt a system of boosted feeders, since in this case the increase in the load-factor on the sub-stations, together with the lower capital charges on the sub-stations, will more than compensate

* When a train is starting from station B, two-thirds of the starting current will be supplied by sub-station A, and the remaining one-third by sub-station D. (This assumes equal voltages at the sub-stations.) Hence the voltage drop in the conductor rail will be: $\left(40 \times \frac{2560}{1725} \times \frac{1200}{1800} =\right) 39.2$ volts.

for the cost of the boosters and feeders. In this connection, the curves of Fig. 477 * are of interest. These curves show the relation between the most economical spacing of the sub-stations and the density of the traffic for a 36-mile double-track railway, having passenger stations one mile apart, on which is run a service of 100-ton trains at a schedule speed of 16 ml.p.h., with stops of 20 to 30 seconds duration. The effect of the operating voltage on the sub-station spacing is also shown.

Sectionalisation of the Distributing System.—With continuous-current railways operating from conductor rails there are no Board of Trade regulations limiting the length of the sections, and consequently the latter can be arranged to suit the requirements of the traffic, due consideration being given to the sectionalisation at cross-overs and junctions.

The methods of sectionalising the conductor rails will obviously be influenced by the method of operating adjacent sub-stations (i.e. whether

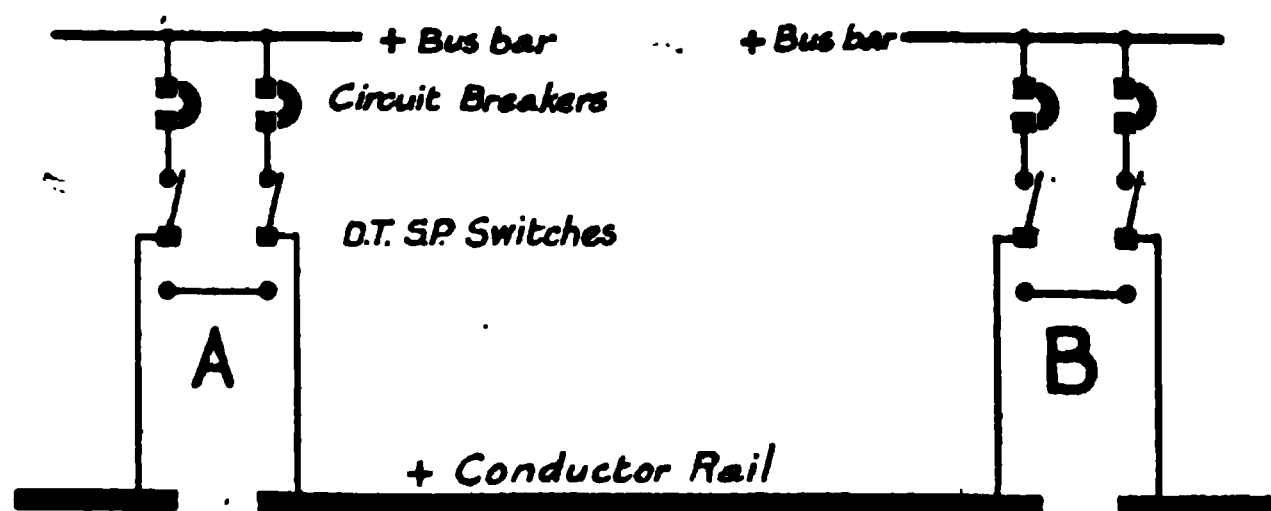


FIG. 478.—Method of Feeding Conductor Rails with Sub-stations operating in Parallel.

these sub-stations are operated in parallel or separately) and will of course depend on whether or not the "up" and "down" conductor rails of the same polarity are cross-bonded.

As examples of cases in which the adjacent sub-stations are operated in parallel we may consider the general scheme of feeding and sectionalisation adopted on the Central London (Tube) and the Metropolitan District (London) Railways.

On the **Central London Railway**, a section-insulator is inserted in the conductor rail opposite each sub-station, and the ends of the conductor rails are connected to double-throw (single-pole) switches, as shown in Fig. 478. When the switches in adjacent sub-stations are thrown into the upper contacts, the section of conductor rail between these sub-stations is fed from each end, and the load on this section is therefore supplied from both of the sub-stations. In the event of one sub-station being shut down, the switches are thrown into the lower contacts, thereby bridging the section-insulators and transferring the load to the sub-stations on either side.

This method of sectionalisation, however, is not suitable when the traffic is operated with motor-coach trains having a power cable (or

* From a paper on the "Economics of Electric Railway Distribution," by Dr. H. F. Parshall. See *Minutes of the Proceedings of the Institution of Civil Engineers*, vol. 199, p. 47. The paper deals very fully with the spacing of sub-stations for various conditions of traffic and various systems of distribution.

“bus line”) between the end motor-coaches,* since if a fault occurred when the train was passing over the section-insulator, the circuit breakers on both sections would be tripped, thereby cutting off power from a considerable length of track. This objection can be removed by inserting a separate section (the length of which is slightly greater than the extreme distance between the front and rear collector shoes) between the main sections, and feeding this section separately. Thus, in Fig. 479, two sub-stations are represented at A and B. Sub-station A

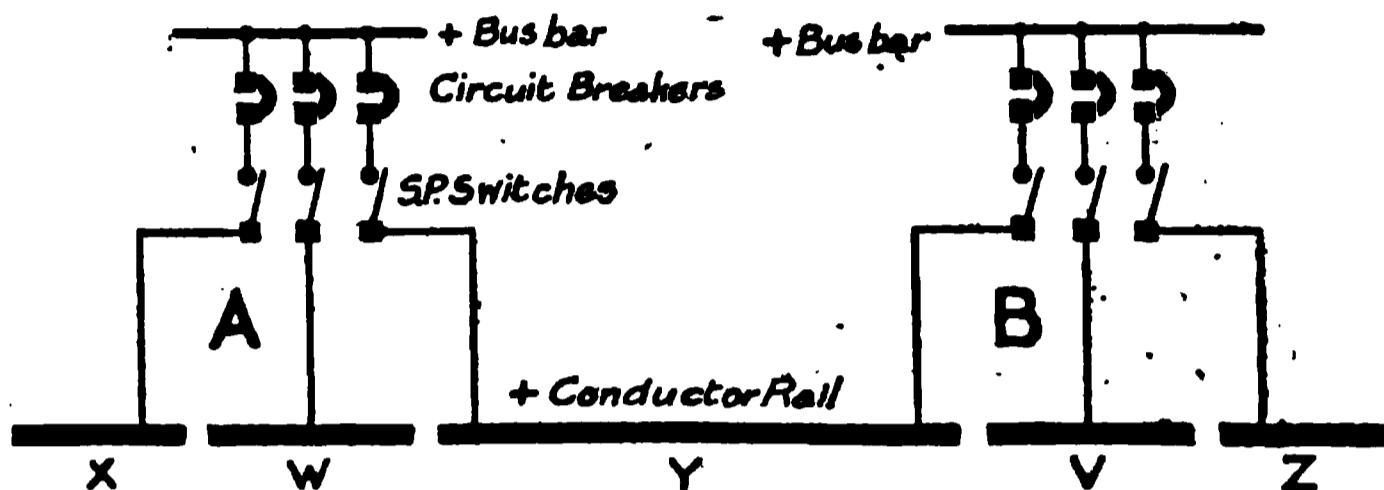


FIG. 479.—Method of Feeding Conductor Rails and “Train Sections” with Sub-stations operating in Parallel.

supplies the sections X, W, Y, while sub-station B supplies the sections Y, V, Z. Of these sections, X, Y, Z represent the main sections of the conductor rails, while W, V represent the special short sections (called “train sections”) opposite each sub-station. It is apparent that an overload on a main section only, or a main section and a train section

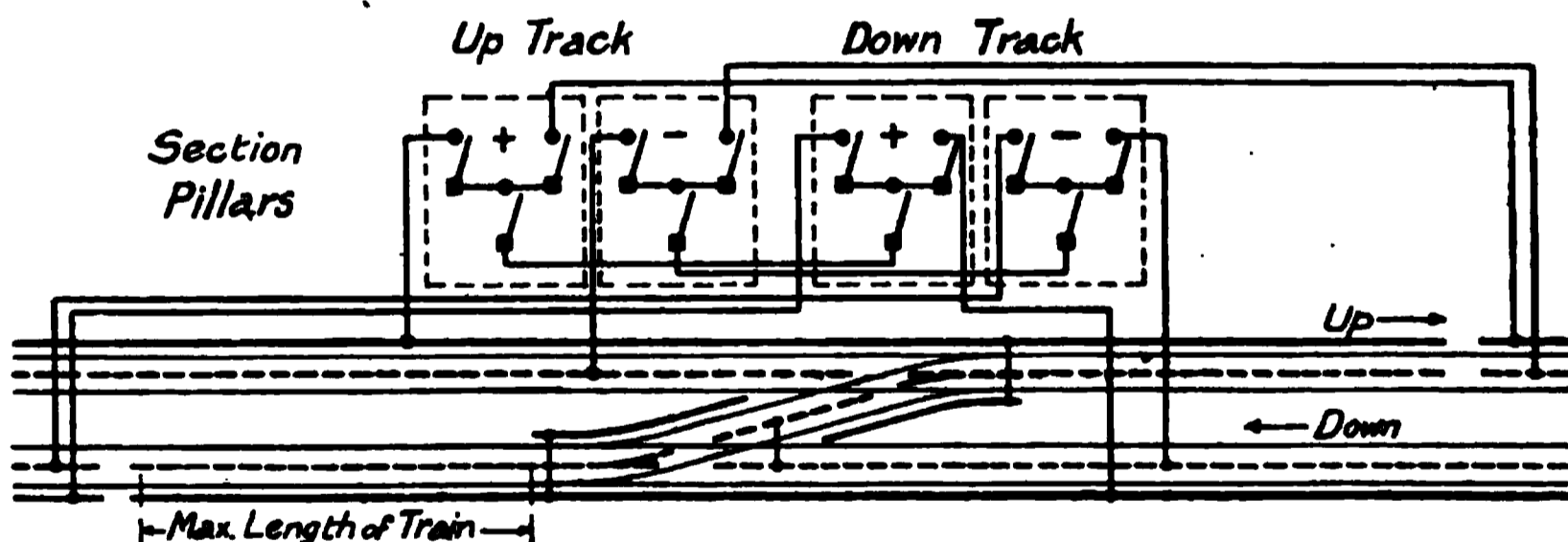


FIG. 480.—Arrangement of Conductor Rails and Sectionalising Switches at a Cross-over.

together, will only shut down one main section. This method of feeding and sectionalising the conductor rails is adopted on the **Metropolitan District Railways**.

In cases where the sub-stations do not operate in parallel—as, for example, on the electrified (London) lines of the **Great Western Railway**—provision must be made for bridging the sections supplied from neighbouring sub-stations, so that, in an emergency, these sections can be supplied from one sub-station. The switches for this purpose are generally located in section pillars adjoining the track.

* On tube railways, no power cable is allowed to be carried between the motor-coaches.

Another feature in which a system supplied from separate sub-stations differs from one in which the sub-stations operate in parallel is the **cross-bonding of the conductor rails** of the same polarity. This cross-bonding is usually carried out by switches located in pillars adjacent to signal cabins, so that the switches may be operated by the signaller on instructions from the responsible department. Under normal conditions of operation the switches are closed, and the "up" and "down" conductor rails of the same polarity are connected together at a number of points, so that the full conductivity of the conductor rails is available.

The method of sectionalising and feeding the conductor rails at **station cross-covers** is important, as provision must be made, in the case of a breakdown, for single-line working or for shuttle working, according to the character of the breakdown. A diagram showing the switches and conductor rail sections to fulfil these requirements is shown in Fig. 480.

FEEDING AND DISTRIBUTING SYSTEMS FOR ALTERNATING-CURRENT RAILWAYS

On alternating-current railways the trains are supplied from overhead contact lines, and the track rails are used as the return conductor. As high operating voltages are adopted, it is apparent that the sub-stations may be placed at considerable distances apart, while, in some cases, sub-stations may be unnecessary. In cases where power is purchased from a company, it may be necessary to instal transformers or frequency changers in the sub-stations for supplying the railway at a suitable voltage and frequency.

The **calculation of the voltage drop** in the overhead contact wire (or trolley-wire) involves the consideration of the effects of resistance, self-induction, mutual-induction, and power-factor. The effect of the power-factor on the voltage drop is shown in the vector diagram of Fig. 481. In this diagram the current (I) is represented by the vector OI , the voltage at the distant (or receiving) end of the line is represented by the vector OV , and the voltage at the generating end of the line is represented by the vector OE , which is compounded from OV and the impedance voltage VE , the latter consisting of the reactance, or inductive, component $Va (=Ix)$ and the resistance component $aE (=Ir)$, capacity effects not being considered.

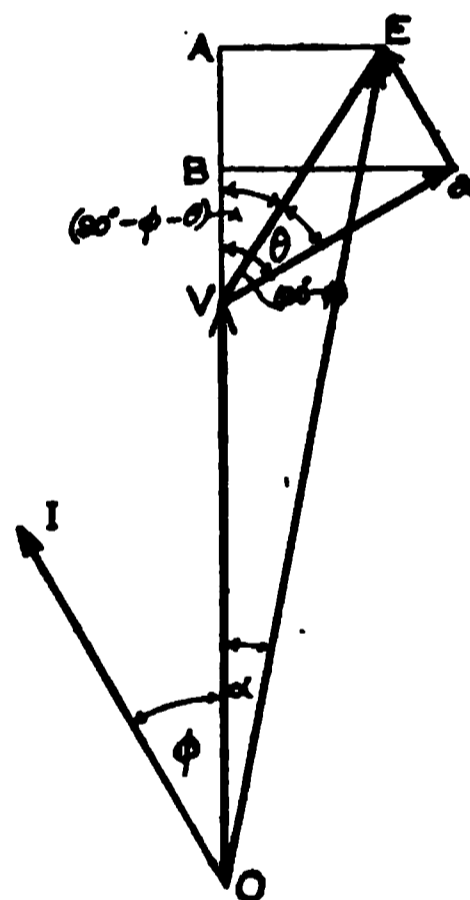


FIG. 481.

Now the difference between OE and OV (i.e. the actual voltage drop v) is given approximately by:

$$v = I(x \sin \phi + r \cos \phi), \quad \dots \dots \dots (59)$$

or
$$v = Iz \cos (90^\circ - \phi - \theta),^* \quad \dots \dots \dots (59a)$$

* With small values for α (Fig. 481), OA and OE are approximately equal. Therefore $OE - OV$ is approximately equal to $OA - OV = VA$.

Now $\angle E\hat{V}A = 90^\circ - \phi - \theta$, and $VE = Iz$, so that $VA = Iz \cos (90^\circ - \phi - \theta)$.

Again, $VA = VB + BA = (xI \cos (90^\circ - \phi) + rI \cos \phi)$
 $= I(x \sin \phi + r \cos \phi)$.

In practice, α is only a small angle, since the impedance voltage (z) is only a

where I is the current; x , r , z are respectively the reactance, the resistance, and the impedance of the circuit; ϕ is the phase-difference between the current and voltage at the receiving end, and θ is the angle between the impedance and reactance voltages.

[NOTE.— θ may be called the characteristic angle of the circuit, since it is given by $\tan^{-1} \frac{\text{resistance}}{\text{reactance}}$.]

The reactance voltage (xI) is given by ωLI , where $\omega = 2\pi f$ (f being the frequency) and L is the inductance of the circuit.

Now L can be calculated from the dimensions and spacing of the conductors forming the circuit. In the case of two parallel wires of radius r , spaced at a distance D apart, the inductance (in henries) per mile of circuit is given by

$$L = 0.00161 \left(0.92 \log \frac{D-r}{r} + 0.1\mu \right) \quad . \quad . \quad . \quad . \quad (60)$$

or approximately by

$$L = 0.00161 \left(0.92 \log \frac{D}{r} + 0.1\mu \right) \quad . \quad . \quad . \quad . \quad (60a)$$

where μ is the permeability of the conductor ($\mu = 1$ for all non-magnetic materials).

[NOTE.—The first term in the bracket refers to the magnetic field external to the conductors, while the second term (0.1μ) refers to the magnetic field inside the conductors.]

In alternating-current railways the trolley-wire and rails differ considerably in dimensions and magnetic properties; consequently the inductance of a circuit consisting of a length of trolley-wire and rails cannot be determined directly by the application of equation (60). It will be necessary, therefore, to calculate the inductance of each part of the circuit separately. Now the self-inductance of a *single* straight wire (removed from the return conductor) is given (in henries) by

$$L_s = \frac{2l}{10^9} \left(\log_e \frac{2l}{r} - 1 + \frac{\mu}{4} \right) = \frac{2l}{10^9} \left(2.3 \log \frac{2l}{r} - 1 + \frac{\mu}{4} \right) \quad . \quad . \quad . \quad . \quad (61)$$

in which l and r denote respectively the length and radius of the wire in centimetres. If the return current passes through a parallel wire of similar dimensions, then the self-inductance of the outgoing wire will be reduced, due to the mutual induction of the return conductor, the reduction in the self-inductance being given (in henries) by:

$$L_m = \frac{2l}{10^9} \left(2.3 \log \frac{2l}{D} - 1 \right),$$

where D is the distance between the wires.

small fraction of the line voltage, and consequently we may apply the above equations to practical problems.

$$\left[\text{NOTE.—} \alpha = \sin^{-1} \frac{z}{OE} \left(\sin 90^\circ - \phi - \theta \right). \right]$$

[Hence the inductance of a wire forming part of a circuit consisting of two parallel wires will be given by :

$$\begin{aligned} L_s - L_m &= \frac{2l}{10^9} \left(2.3 \log \frac{2l}{r} - 1 + \frac{\mu}{4} - 2.3 \log \frac{2l}{D} + 1 \right) \\ &= \frac{2l}{10^9} \left(2.3 \log \frac{D}{r} + \frac{\mu}{4} \right), \end{aligned}$$

from which the inductance per mile of circuit is obtained as :

$$\begin{aligned} L &= \frac{4}{10^9} \left(2.3 \log \frac{D}{r} + \frac{\mu}{4} \right) \times 1.61 \times 10^5 \\ &= 0.00161 \left(0.92 \log \frac{D}{r} + 0.1\mu \right). \end{aligned}$$

Now, if the return circuit consist of two wires parallel to the outgoing wire, then each of the return conductors will exert an inductive effect upon the outgoing wire. Hence if I , I_1 , I_2 denote the currents in the outgoing and return conductors ; r_0 , r_1 , r_2 denote the respective radii of these conductors ; and D_1 , D_2 denote the distance between the outgoing and each return conductor ; then, since $I = (I_1 + I_2)$, the inductance of a length l (cms.) of the outgoing conductor will be given by :

$$\begin{aligned} L_o &= \frac{2l}{10^9} \left\{ \left(2.3 \log \frac{2l}{r} - 1 + \frac{\mu}{4} \right) - \left(2.3 \log \frac{2l}{D_1} - 1 \right) \frac{I_1}{I} - \left(2.3 \log \frac{2l}{D_2} - 1 \right) \frac{I_2}{I} \right\} \\ &= \frac{2l}{10^9} \left\{ \frac{\mu}{4} + 2.3 \left(\log \frac{2l}{r} - \frac{I_1}{I} \log \frac{2l}{D_1} - \frac{I_2}{I} \log \frac{2l}{D_2} \right) - 1 + \frac{I_1}{I} + \frac{I_2}{I} \right\} \\ &= \frac{2l}{10^9} \left\{ \frac{\mu}{4} + 2.3 \log \left(\frac{D_1^{\frac{I_1}{I}} \times D_2^{\frac{I_2}{I}}}{r} \right) \right\} \quad \dots \dots \dots (62) \end{aligned}$$

The inductance of one of the return conductors (say No. 1) will be given by :

$$\begin{aligned} L_1 &= \frac{2l}{10^9} \left\{ \left(2.3 \log \frac{2l}{r_1} - 1 + \frac{\mu_1}{4} \right) - \left(2.3 \log \frac{2l}{D_1} - 1 \right) \frac{I}{I_1} + \left(2.3 \log \frac{2l}{D_3} - 1 \right) \frac{I_2}{I_1} \right\} \\ &= \frac{2l}{10^9} \left\{ \frac{\mu_1}{4} + 2.3 \log \left(\frac{D_1^{\frac{I}{I_1}}}{r_1 \times D_3^{\frac{I_2}{I_1}}} \right) \right\}, \end{aligned}$$

where D_3 is the distance between the two return conductors. Similarly, the inductance of the other return conductor (No. 2) will be given by :

$$L_2 = \frac{2l}{10^9} \left\{ \frac{\mu_2}{4} + 2.3 \log \left(\frac{D_2^{\frac{I}{I_2}}}{r_2 \times D_3^{\frac{I_1}{I_2}}} \right) \right\}.$$

If the return conductor acted also as the return conductor for a second outgoing wire, then the above equations would have to be modified to take into account the mutual induction of this wire upon the other outgoing wires and the return conductors.

It is apparent that, in the case of a double or four-track single-phase railway, the calculation of the voltage drop in the rails and the trolley-wire is not a simple process. As an **example** of the application of the above equations we will consider the case of a single-track railway on which the trolley-wire is suspended centrally above the rails. The two

80-lb. track rails are laid to standard gauge (4 ft. 8.5 in.), and are cross-bonded. The copper trolley-wire is 0.5 in. in diameter, and is 17 ft. above the rails.

If the distance between the centres of the rails be assumed as 4.9 ft., the distance between the trolley-wire and one rail will be $(\sqrt{17^2 + 2.45^2} =) 17.17$ ft. Hence, on account of the symmetrical arrangement of the trolley-wire and rails, the inductive effect of the latter on the former will be the same as if the return current passed through a single conductor 17.17 ft. below the trolley-wire.

The inductance of 1 mile of the trolley-wire is therefore

$$\frac{2 \times 1.61 \times 10^5}{10^9} \left(0.25 + 2.3 \log \frac{17.17 \times 12}{0.25} \right) = 0.00223 \text{ henries.}$$

In order to calculate the inductance of the rail return we must know (1) the equivalent radius of the rails and (2) the permeability.

The former may be taken as equal to $\left(\frac{1}{2\pi} \times \text{perimeter of rail} \right)$, the perimeter of standard bull-head rails being given in Table XXIV (p. 492).

The permeability depends on the chemical composition of the rail, and on the current passing through it. In the present example we will assume the perimeter of the rail as 18.8 in., and the permeability as 40. Hence the inductance per mile of the rail return will be:

$$\frac{1}{2} \times \frac{2 \times 1.61 \times 10^5}{10^9} \left\{ \frac{40}{4} + 2.3 \log \left(\frac{17.17^2}{\frac{18.8 \times 4.9}{2\pi \times 12}} \right) \right\} = 0.0025 \text{ henries.}$$

[NOTE.—The index 2 in the logarithmic term is obtained from the ratio of the current in the trolley-wire to the current in one rail, each rail being assumed to carry one-half of the current in the trolley-wire.]

The impedance of the trolley-wire and the rails can be obtained when the resistances and the frequency are known. The resistance of the track rails, however, will not be equal to the resistance as measured with continuous currents, on account of the “skin effect” (i.e. the concentration of the current to the outer portion of the rail).

Now the “**skin effect**” depends on the frequency and the magnetic properties of the conductor. In the case of conductors consisting of magnetic materials, the current is confined to a thin surface layer of the conductor, the thickness (δ) of which is given by

$$\delta = \sqrt{\frac{\rho}{2\pi\mu\omega}},$$

where ρ denotes the specific resistance of the material, μ the permeability, and $\omega = 2\pi \times \text{frequency}$.

From a number of tests * on track rails carrying alternating currents, the thickness of the surface layer has been computed at from 3 to 4 millimetres for the frequencies and currents appropriate to alternating-current railways. The equivalent resistance of the track rails when carrying alternating currents may therefore be calculated from δ , ρ , and the perimeter (p) of the rail.

Assuming $\delta = 3$ mm. and $\rho = 8 \times 10^{-6}$ ohms per inch cube, the equi-

* See *The Electrician*, vol. 56, p. 757.

valent resistance (R) per foot of rail is given by $R = \frac{813}{p} \times 10^{-6}$ ohms, p being the perimeter of the rail in inches.

We are now able to calculate the impedance of the track rails in the above example. Thus, the equivalent resistance of a mile of the above single track, cross-bonded, is $\left(1.2 \times \frac{5280}{2} \times \frac{813}{18.8} \times 10^{-6} =\right) 0.15$ ohm.

[NOTE.—20 per cent. is allowed for the resistance of the joints.]

Hence the impedance of the rail return at 25 frequency

$$= \sqrt{(0.15)^2 + (2\pi \cdot 25 \times 0.0025)^2} = 0.395 \text{ ohm per mile.}$$

Therefore the voltage drop in the rails, when carrying a current of 120 amperes, will be $(120 \times 0.395 =) 47.4$ volts per mile.

With a number of trains on this length of track, the voltage drop would reach an undesirable value. Therefore provision must be made

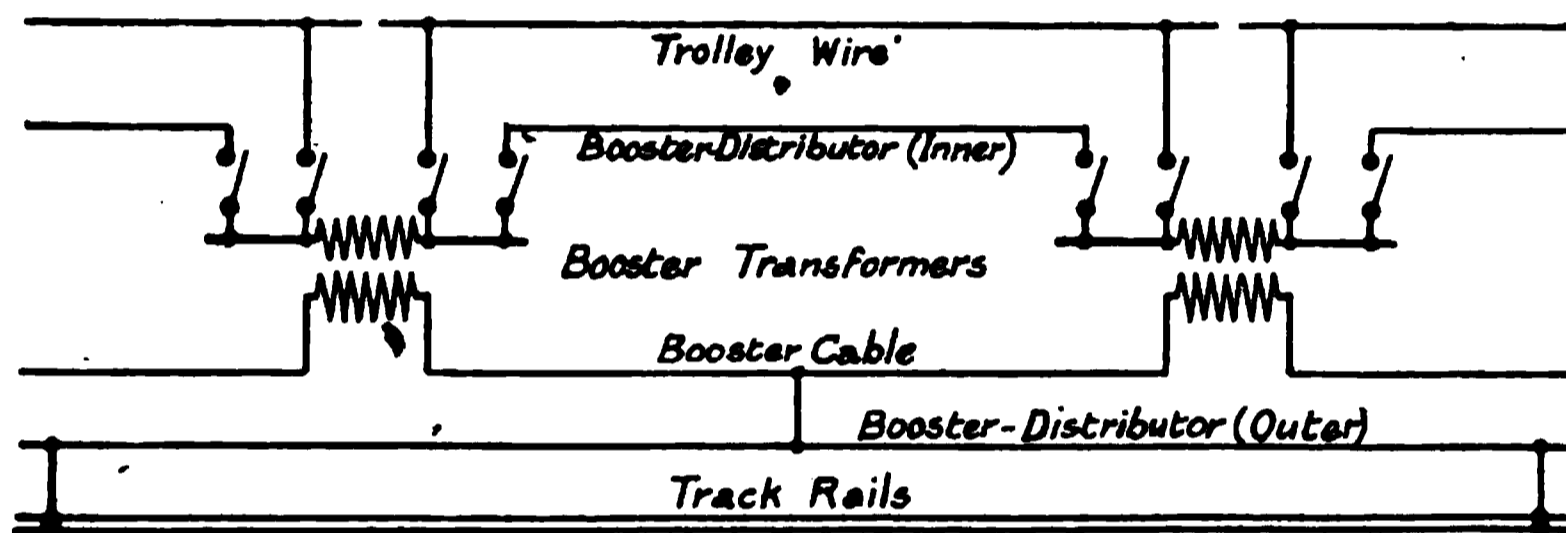


FIG. 482.—Method of Connecting Booster-transformers for Neutralising Voltage Drop in Rails.

for relieving the rails of some of the return current, so that the maximum voltage drop in the rails will not exceed 20 volts.

This result can be obtained by the use of **booster-transformers** in connection with a concentric distributing cable. Although various **methods of arranging the boosters and cables** are possible, we shall only consider the method which is in use in this country (on the suburban lines of the London, Brighton, and South Coast Railway). This method is shown diagrammatically in Fig. 482.

Referring to Fig. 482, the sections of the trolley-wire are supplied from the inner conductor of a concentric cable, which is divided up into the same number of sections as the trolley-wire, the sections being connected through the primary windings of the booster-transformers (of 1 : 1 ratio). Thus the primary windings of the booster-transformers are all connected in series. The secondary windings of the booster-transformers are also connected in series by a single insulated cable, which is connected at certain points to the (earthed) outer conductor of the concentric cable, this conductor being also connected to the rails at frequent intervals.

Now, since the booster-transformers have a ratio of unity, the primary and secondary currents will be nearly equal (the difference between these currents being equal to the magnetising current of the transformers), and consequently the cable connecting the secondary windings of the

transformers must carry a current approximately equal to that in the inner conductor of the concentric distributing cable. Therefore practically all the return current will be drawn from the rails into the booster cable.

The E.M.F. in the secondary winding of the booster-transformers (which neutralises the impedance voltage drop in the secondary circuit) is obtained from the primary winding, so that the voltage drop in the return conductor is transferred to the outgoing conductor (i.e. the inner conductor of the concentric distributing cable).

METHODS OF FEEDING AND SECTIONALISING THE TROLLEY-WIRE

In single-phase railways the percentage permissible variation of voltage at the trains is much greater than that for continuous-current or three-phase railways, since the methods of control adopted for single-phase motors are generally arranged so that the schedule speed can be maintained with the line voltage considerably below normal. For instance, it is only necessary to provide additional tapplings on the main transformer, and one or two extra notches on the controller. With three-phase motors, supplied direct from the trolley-wires, the variation of the line voltage affects the performance of the motor—the torque for a given current varying approximately as the square of the line voltage—so that abnormally low voltages must be avoided.

It is apparent, therefore, that a considerable length of track can be supplied from one feeder, and that a large spacing of the sub-stations (when these are necessary) may be adopted.

But the trolley-wire must be divided into sections, which must be interconnected so that the train service may be maintained in the case of the breakdown of one section. The switches for this purpose may be located in cabins adjoining the signal cabins (as on the London, Brighton, and South Coast Railway), or they may be placed on the top of the gantries (as on the New Haven Railroad).

The general scheme of feeding and sectionalising the trolley-wire on the **London, Brighton, and South Coast Railway** is as follows: The power is purchased from a supply company, and is supplied at the required voltage and frequency (viz. 6600 volts, 25 frequency) to a central distributing room, from which it is distributed to the various parts of the overhead system. The South London lines (London Bridge-Victoria) are supplied from the central distributing room (which is situated at one of the passenger stations on that line), while the Victoria-Crystal Palace lines are supplied from another distributing room, which receives power from the central distributing room through a concentric feeder (0·5 sq. in.).

The sections of the trolley-wire are supplied from the distributing rooms by means of concentric distributors, the inner conductor of which is connected to the bus-bars in the switch cabins, and the outer conductor is connected to the rails and gantries.

The **switch cabins** are generally placed near the passenger stations. Each cabin is equipped with a booster-transformer, and the necessary oil-switches, disconnecting switches, and lightning arresters. The high-tension bus-bar is divided into two sections, which are connected through the primary winding of the booster-transformer. Each transformer is

provided with short-circuiting and disconnecting oil-switches on the high-tension side, and a short-circuiting switch on the low-tension side. The secondary windings of the booster-transformers are interconnected by



FIG. 483.—Sectionalising Gantry and Switch Cabin (L.B. and S.C. Railway).

a single insulated cable, which is connected at certain points to the outer conductor of the distributor.

The arrangement of the external wiring from the switch cabin to the

various sections of the trolley-wire is shown in Fig. 483. The sections of the trolley-wire are connected to insulated transverse wires, suspended over the top of the gantry, and the latter wires are connected to the section switches in the cabin, the outlets being arranged in the roof.

Interference Effects on Telegraph and Telephone Circuits.—It is clear that, when telegraph and telephone circuits are run parallel to trolley-wires carrying single-phase currents, the latter will produce electromagnetic and electrostatic disturbances in the former. In some cases the disturbances have been of such magnitude that the telephone circuits have had to be run underground, and in other cases various devices have had to be adopted to neutralise the inductive effects in the auxiliary circuits.*

In the case of an extensive railway system, where the gantries are used for carrying overhead feeders as well as the trolley-wires (see Figs.

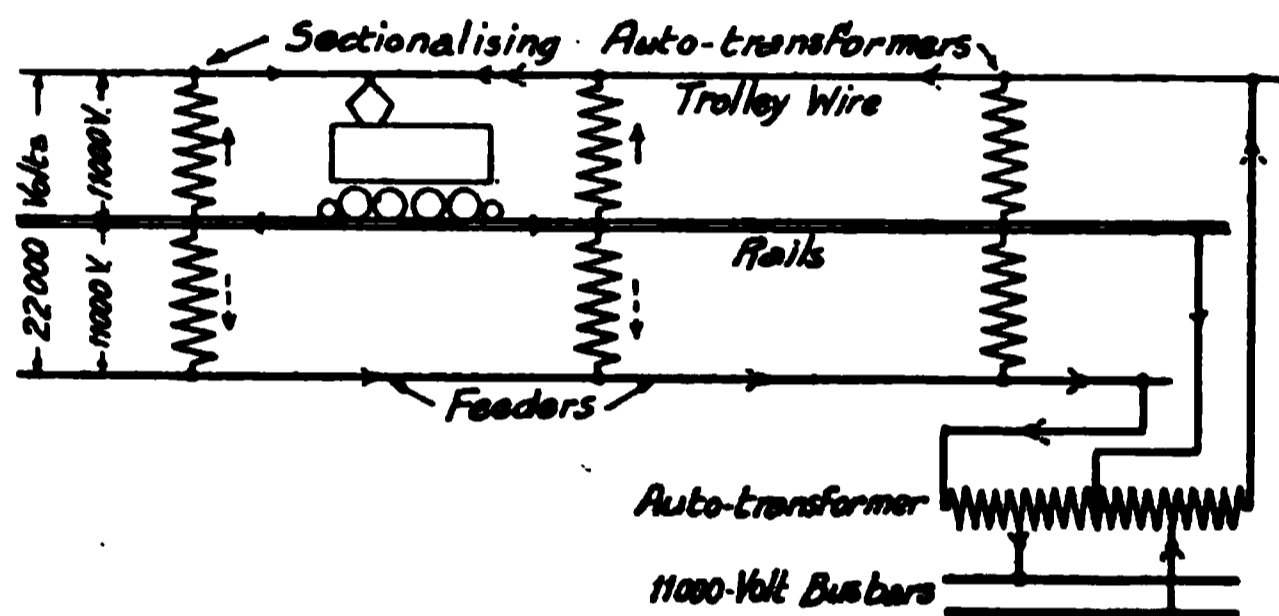


FIG. 484.—Method of Connecting Overhead Feeders and Trolley-wire to Minimise Interference Effects on Neighbouring Circuits.

451, 454, pp. 550, 553), the electromagnetic disturbances in the parallel auxiliary circuits may be minimised by adopting the distributing system shown diagrammatically in Fig. 484. In this system (which is adopted on the extensive electrification of the **New York, New Haven, and Hartford Railroad** and its branches) the feeders are supplied at double the voltage of the trolley-wire, and the latter is fed from the former through auto-transformers. The centre point of the winding of each auto-transformer is connected to the rails. Consequently, the electromagnetic effects, due to the currents in the feeders and trolley-wires, partially neutralise each other. Moreover, the currents in the portions of the trolley-wire between adjacent transformers are in opposite directions—as shown in Fig. 484—so that the resultant inductive effect on a neighbouring circuit will be practically zero. The arrangement of the feeders and trolley-wires also minimises the electrostatic effects on neighbouring circuits.

On the New Haven electrified lines † the auto-transformers are of

* In this connection see *Proceedings of the Institution of Civil Engineers*, vol. 179, p. 58; *Journal of the Institution of Electrical Engineers*, vol. 51, pp. 522, 570, 634; *Journal of Post Office Engineers*, 1915.

See *The Electrician*, vol. 63, p. 208, for the effect of harmonics caused by the motors.

† For a diagram of the auto-transformer sub-stations, and the feeders, see *The Electric Journal*, vol. 11 (1914), p. 253. See also *The Electrician*, vol. 73, p. 130.

the outdoor type, and are placed alongside the track at intervals of from 2 to 8 miles, according to the density of the traffic. The sectionalising switches—which also form overload circuit-breakers—are

FIG. 485.—Sectionalising Gantry and Outdoor Auto-transformer Sub-station (N.Y., N.H., and H.R.R.).

of the electrically-operated oil-break type, and are placed on the top of the sectionalising gantries, the switches being controlled from an adjacent signal cabin. A typical sectionalising gantry, showing the switches and the outdoor auto-transformer sub-station, is shown in Fig. 485.

CHAPTER XXVII

SUB-STATION CONVERTING MACHINERY AND SWITCHGEAR FOR CONTINUOUS-CURRENT TRAMWAYS AND RAILWAYS

THE supply of continuous current to extensive tramway and railway systems cannot be effected economically from a central continuous-current power station, on account of the low voltage of transmission. Moreover, in many cases, a central site for the power station would not be available. Therefore, it will be necessary to adopt a high-voltage transmission system with sub-stations, from which the power is distributed to the low-tension network. Since the most economical system of transmission is by means of three-phase alternating currents, the sub-stations must contain rotating machinery* for the conversion of the alternating current into continuous current. The machinery available for this purpose comprises: (1) rotary converters, (2) motor-generators, (3) motor-converters.

Of these machines, the **motor-generator** is the simplest but the least efficient: it consists of an alternating-current motor direct-coupled to a continuous-current generator. The motor may be wound for the full supply voltage (when this does not exceed 10,000 volts), and the voltage of the generator may be regulated in the usual manner. There is, therefore, no fixed relation between the voltages of the continuous-current and alternating-current sides, and obviously, the frequency of the supply system does not affect the operation of the generator.

The **rotary converter** (sometimes called a synchronous converter) is considered in detail below. For present purposes, we may state that the rotary converter is a single machine, consisting of a stationary field-magnet system and an armature with a commutator and slip-rings; the armature winding being usually of the continuous-current multiple-circuit type with connections to the slip-rings at suitable points. The armature winding is, therefore, common to both alternating-current and continuous-current sides. Consequently, a fixed ratio exists between these voltages, and if the voltage at the continuous-current side is required to be varied, the variation must be obtained either by altering the voltage at the alternating-current side, or by changing the wave-form

* It is probable that in the near future the mercury-vapour converter (or rectifier) will be available for sub-stations supplying high-voltage continuous-current railways. This apparatus is now being developed in large sizes, and a 1000 kw. converter has been in service for some time on the New York, New Haven, and Hartford Railroad; the converter being installed on an electric locomotive. See *The Electrician*, vol. 74, p. 891; *Electric Railway Journal*, vol. 44, p. 1343.

of the flux distribution. Since the voltage at the alternating-current side is lower than that at the continuous-current side; transformers will be required for operating the machine from a high-voltage supply circuit.

When supplied with alternating current, the rotary converter is essentially a synchronous machine, and it possesses characteristics and operating features which are common to synchronous machinery: for example, the machine is liable to surge, or "hunt," with variations in the supply frequency, and to drop out of step with excessive overloads or short-circuits on the supply system. These phenomena are generally accompanied by sparking and flashing over at the continuous-current side, and are more pronounced in machines operating on circuits of high frequency (*e.g.* 50 and 60 cycles).

The **motor-converter** (sometimes called a cascade converter) consists of two machines, which are coupled together mechanically and electrically. In principle, the machine is an induction motor and a rotary converter connected in cascade; the induction motor forming the primary element of the group. The speed of the set is, therefore, dependent on the sum of the numbers of poles on both machines (see Chapter XI, p. 104).

The motor-converter possesses operating features which are, in some respects, superior to those of the rotary converter. Thus, the voltage of the continuous-current side can be regulated over a moderate range—10 per cent. up or down—and the alternating-current side can be supplied with high voltage. The efficiency of the motor-converter, however, is lower than that of the rotary converter, but is higher than that of the motor-generator.

In any given case the **choice of the converting machinery** will be influenced by the frequency of the supply, and the continuous-current voltage. With modern power plants, in which large turbo-generators are adopted, the operation of rotary converters, of modern design, is perfectly satisfactory for continuous-current voltages up to 1500 volts—when the supply is at 25 frequency—and for voltages up to 750 volts when the supply is at 50 or 60 frequency. When higher voltages are required, it is general practice to instal motor-generators, although, in some cases two rotary converters connected in series have been adopted.

Confining our attention to continuous-current voltages between 500 and 750 volts, the above machines may be considered on an equality as far as normal operation is concerned. Hence the choice of plant will be influenced by considerations of: (1) efficiency; (2) space occupied; (3) cost.

The comparison between the above machines for efficiency is shown in Fig. 486, which represents the approximate difference in efficiency between (a) rotary converters and motor-generators, (b) rotary converters

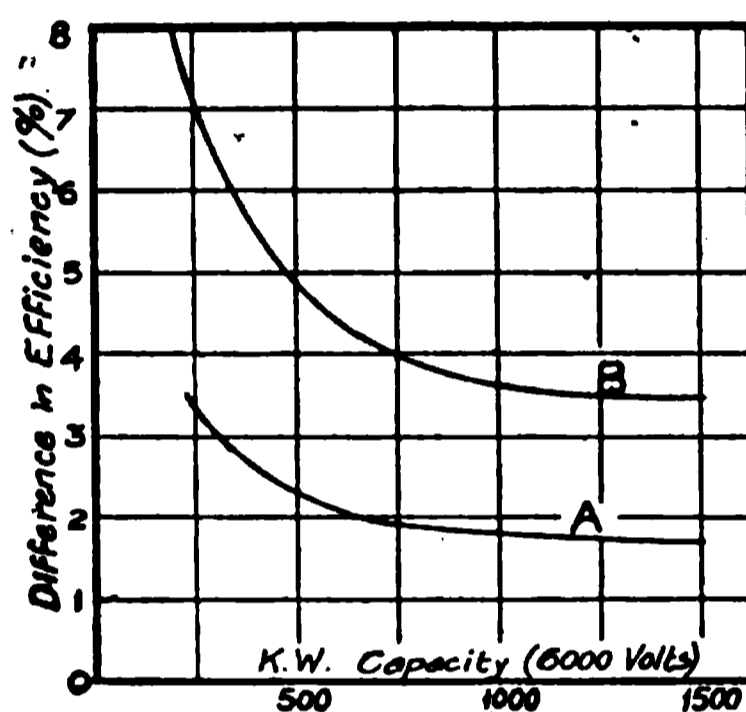


FIG. 486.—Difference in Efficiency between (A) Rotary Converter and Motor-converter, (B) Rotary Converter and Motor-generator.

and motor-converters; the rotary converters being supplied through transformers, and the motor-generators and motor-converters being supplied direct from the supply system (at 6000 volts). It will be observed that the difference in efficiency increases rapidly as the size of the machines is reduced.

As comparative values for the efficiencies of modern rotary converters and motor-generators for railway purposes, the following are representative:—

(a) 1500 kw., 10-pole, 25 frequency, 600-volt rotary converter (with transformers).

Percentage of full load	50	75	100	125	150
Percentage efficiency	93	94.3	94.5	94.2	93.1

(b) 1500 kw., 14-pole, 60 frequency, 600-volt rotary converter (with transformers).

Percentage of full load . . .	50	75	100	125	150	200
Percentage efficiency . . .	90.3	92.9	93.8	94.2	94.2	93.2

(c) 1000 kw., motor-generator set, consisting of 2300-volt, 10-pole, 60 frequency, synchronous motor, and two 500 kw., 1200-volt, continuous-current generators (see Fig. 502).

Percentage of full load	50	75	100	125
Percentage efficiency	87.5	90.4	91.6	91.5

The comparison between the above machines, as regards floor space occupied, is obviously in favour of the rotary converter. When considered without transformers, the floor space required by machines of similar rating (1500 kw.) and speeds (300 to 375 r.p.m.) is approximately as follows: *—

Rotary converter (without starting motor) . . .	84 sq. ft.
Rotary converter (with starting motor) . . .	92 „
Motor-generator	160 „
Motor-converter.	120 „

On account of the differences in the efficiencies of the above machines, the comparison between the initial costs is of relatively small importance, as, even if the rotary converter were more expensive than the other machines, the additional cost would probably be justified on account of the higher efficiency.

The above comparison between rotary converters, motor-generators, and motor-converters is sufficient to indicate the reasons for the preference of rotary converters for traction service, and we now purpose to discuss these machines more in detail † confining our attention to machines for traction service and for voltages between 500 and 750 volts

Voltage Ratio.—It can be shown ‡ that when a rotary converter is running at no load—with sinusoidal flux distribution and sinusoidal

* From a paper by Professor Miles Walker entitled “Rotary Converters *versus* Motor-Generators.” See *Journal of the Institution of Electrical Engineers*, vol. 38, p. 428.

† In this discussion we shall consider the rotary converter from the practical or operating standpoint. For a discussion from the design standpoint (together with examples of designs) see *Alternating Current Machinery*, by Barr & Archibald, Chapters XIII, XIV, XV. (Published by Whittaker & Co.)

‡ *Ibid.*, p. 424.

supply E.M.F.—the ratio of the voltage (E_s) between adjacent slip-rings to the voltage (E) at the commutator is given by :

$$\frac{E_s}{E} = \frac{1}{\sqrt{2}} \sin \frac{\pi}{m},$$

where m is the number of phases into which the armature winding is divided by theappings connected to the slip-rings.

Generally rotary converters are connected for either three or six phases (i.e. the portion of the armature winding corresponding to each pair of poles is divided into three or six parts by equidistantappings), and the theoretical voltage ratios * are :—

$$0.612 \text{ for three phases } \left(0.612 = \frac{1}{\sqrt{2}} \sin \frac{\pi}{3} \right)$$

and $0.354 \text{ for six phases } \left(0.354 = \frac{1}{\sqrt{2}} \sin \frac{\pi}{6} \right)$

The theoretical ratio of the line currents on the assumption of unity power-factor and no losses is given by

$$\frac{I_a}{I_c} = 2\sqrt{2} \frac{\sin \frac{\pi}{m}}{m \sin \frac{\pi}{m}} = \frac{2\sqrt{2}}{m},$$

where I_a , I_c , denote the line currents on the alternating-current and continuous-current sides respectively, and m denotes the number of phases.

For three-phase and six-phase machines the theoretical current ratios are respectively

$$0.943 \left(= \frac{2\sqrt{2}}{3} \right) \text{ and } 0.472 \left(= \frac{2\sqrt{2}}{6} \right).$$

The voltage ratio for six phases refers to the voltage between *adjacent*appings on the armature, which are 60 (electrical) degrees apart.

The voltage ratio forappings 180 (electrical) degrees apart will be the same as that for a single-phase rotary converter $\left\{ \text{i.e. } 0.707 \left(= \frac{1}{\sqrt{2}} \sin \frac{\pi}{2} \right) \right\}$,

while the voltage ratio forappings 120 (electrical) degrees apart will be the same as that for a three-phase rotary converter.

Hence the **voltage ratio for a six-phase rotary converter** may have the values 0.354, 0.707, 0.612, according to the position of theappings between which the alternating-current voltage is measured. This feature will be rendered clear by a reference to Figs. 487 and 488, the former representing the location of theappings for a two-pole six-phase machine, and the latter showing the phase and quantitative relations between the E.M.Fs. It is apparent that the voltages betweenappings 1-4, 3-6, 5-2 (Fig. 487) are equivalent to three single-phase systems differing 120 degrees in phase, while the voltages between theappings

* In practice, the voltage ratio may differ from the theoretical values by values up to approximately 5 per cent. according to the design, the shape of the E.M.F. wave, &c.

1-3-5, 4-6-2 (Fig. 487) are equivalent to two three-phase systems differing 180 degrees in phase.

Therefore a six-phase rotary converter may be supplied either from (1) a six-phase circuit, in which the E.M.Fs. differ 60 degrees in phase and have a magnitude (between lines) of 0.354 of the continuous-current voltage; (2) three single-phase circuits, in which the E.M.Fs. differ 120 degrees in phase and have a magnitude of 0.707 of the continuous-

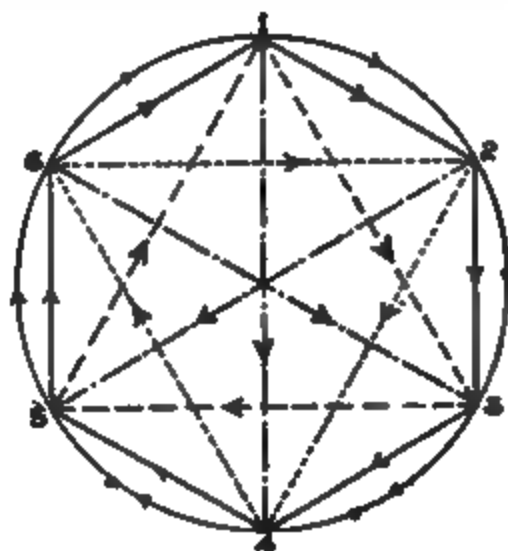


FIG. 487.

FIG. 488.

current voltage; (3) two three-phase circuits, in which the two groups of E.M.Fs. differ 180 degrees in phase, and have a magnitude of 0.612 of the continuous-current voltage.

In order to distinguish these methods of supply they will be referred to respectively as: (1) six-phase mesh, (2) six-phase diametrical, and (3) six-phase double delta.

In practice, the supply in cases (2) and (3) is obtained from a three-

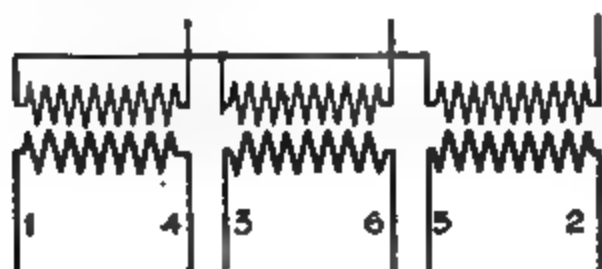


FIG. 489.—Diametrical.

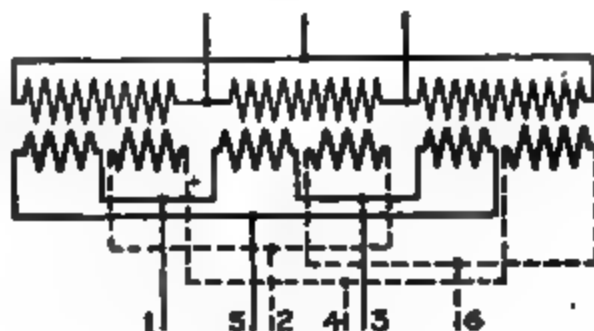


FIG. 490.—Double Delta.

Methods of Connecting Transformers for Supplying Six-phase Rotary Converters from Three-phase Supply System.

phase system by a suitable connection of the transformers. For instance, the three single-phase circuits, differing 120 degrees in phase, are obviously obtained from the secondary windings of a three-phase transformer by removing the interconnections between the secondary phases (see Fig 489), while the two three-phase circuits, differing 180 degrees in phase, are obtained from a three-phase transformer, with double secondary windings, by connecting the corresponding portions of the secondaries in Δ , and reversing one group in relation to the other, as indicated in Fig. 490

In practice, the six-phase diametrical connection is generally adopted, since standard transformers can be used, and interconnections between the secondary windings of the transformers are not required.

Six-phase rotary converters possess several **advantages** over three-phase machines, the principal advantages being (a) that the heating of the armature winding for a given cross-section of armature conductor and a given output is considerably reduced, thereby enabling a greater output to be obtained from an armature of given dimensions; and (b) that the efficiency is slightly higher.

The relation between the **armature heating and the number of phases**, for a given size of armature conductor and a given output, is shown by the curves of Fig. 491. These curves show also the effect of the power-factor on the heating.

The small heating in polyphase rotary converters results from the fact that the armature conductors carry the difference between the continuous and alternating currents. The resultant current in the armature conductors, corresponding to a given output, will therefore be lower the higher the power-factor.

The resultant current is not distributed equally among the armature conductors, but is greatest at the coils from which tappings are made to the slip-rings, this variation of heating being shown in Fig. 492.* It will be observed that the local heating is considerably less with a six-phase machine than with a three-phase machine.

Voltage Regulation.—The voltage ratio of a rotary converter is practically unaffected by changes in the flux † (provided that the waveform of the flux distribution is unaltered), while the ratio only changes slightly with the load. For traction plants it is desirable in some cases for the voltage to increase with the load, in order to compensate for the drop in the continuous-current feeders. The increase in voltage from no load to full load is usually 10 per cent. of the no-load voltage.

With rotary converters this **compounding** effect is usually obtained

* With a given armature winding and a given output, the theoretical ratios between the heating of the winding when operated as a six-phase rotary converter and as a continuous-current generator are :

Average value for all coils (unity power-factor) 0.27 : 1.

Average value for all coils (0.975 power-factor) 0.313 : 1.

Coils connected to slip-rings (unity power-factor) 0.42 : 1.

Coils connected to slip-rings (0.975 power-factor) 0.66 : 1.

† Changes in the flux will, of course, affect the power-factor and alter the current input, which may cause a slight alteration in the voltage ratio, due to the change in the armature I^2R losses.

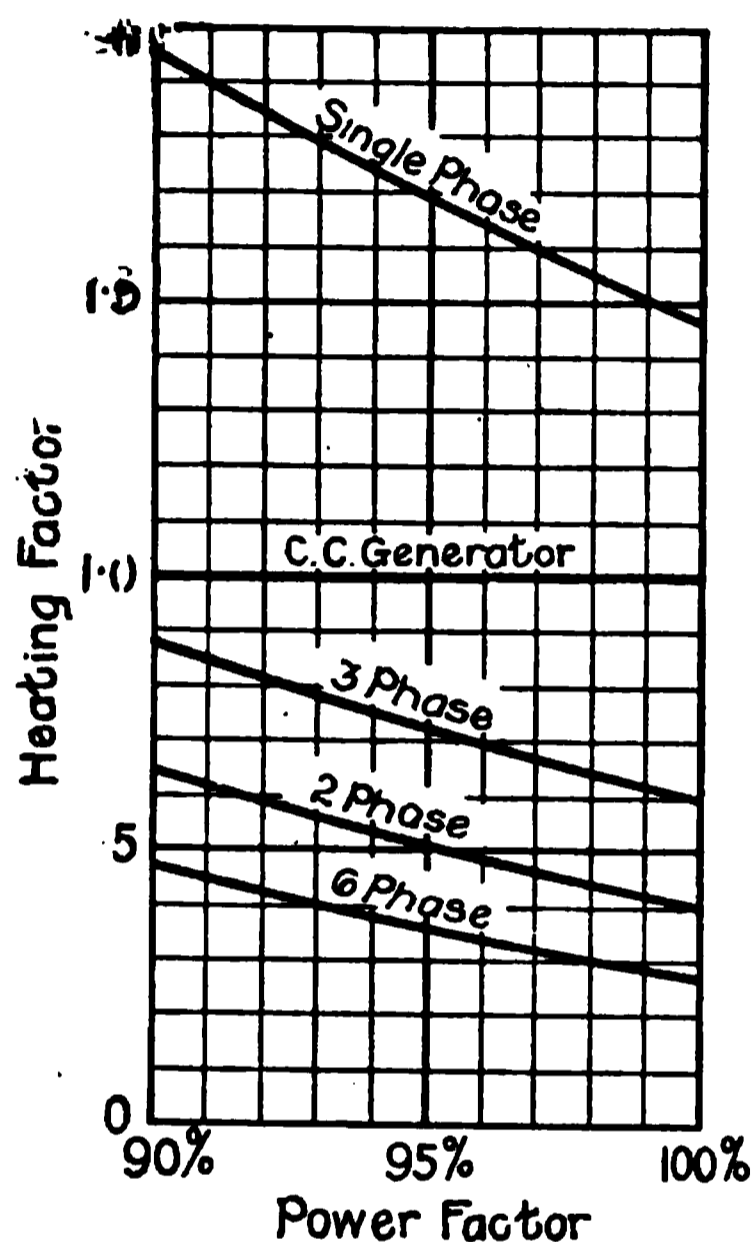


FIG. 491.—Variation of Armature Heating with Power-factor and Number of Phases.

by means of reactance (in the alternating-current side) in conjunction with a compound winding on the machine. The reactance may be inserted in the transformers (as, for example, by increasing the magnetic leakage), or an external reactance coil (connected between the transformer and slip-rings) may be adopted. The object of the compound winding is to produce automatically a variation of the power-factor with the load. For instance, if the shunt excitation is adjusted so that the machine takes a lagging current at no load, the power-factor will increase as the load increases (due to the increase in the excitation). By suitable adjustment of the field rheostat unity power-factor may be obtained at full load; while at overloads the power-factor will decrease, and a leading current will flow into the machine. This variation of

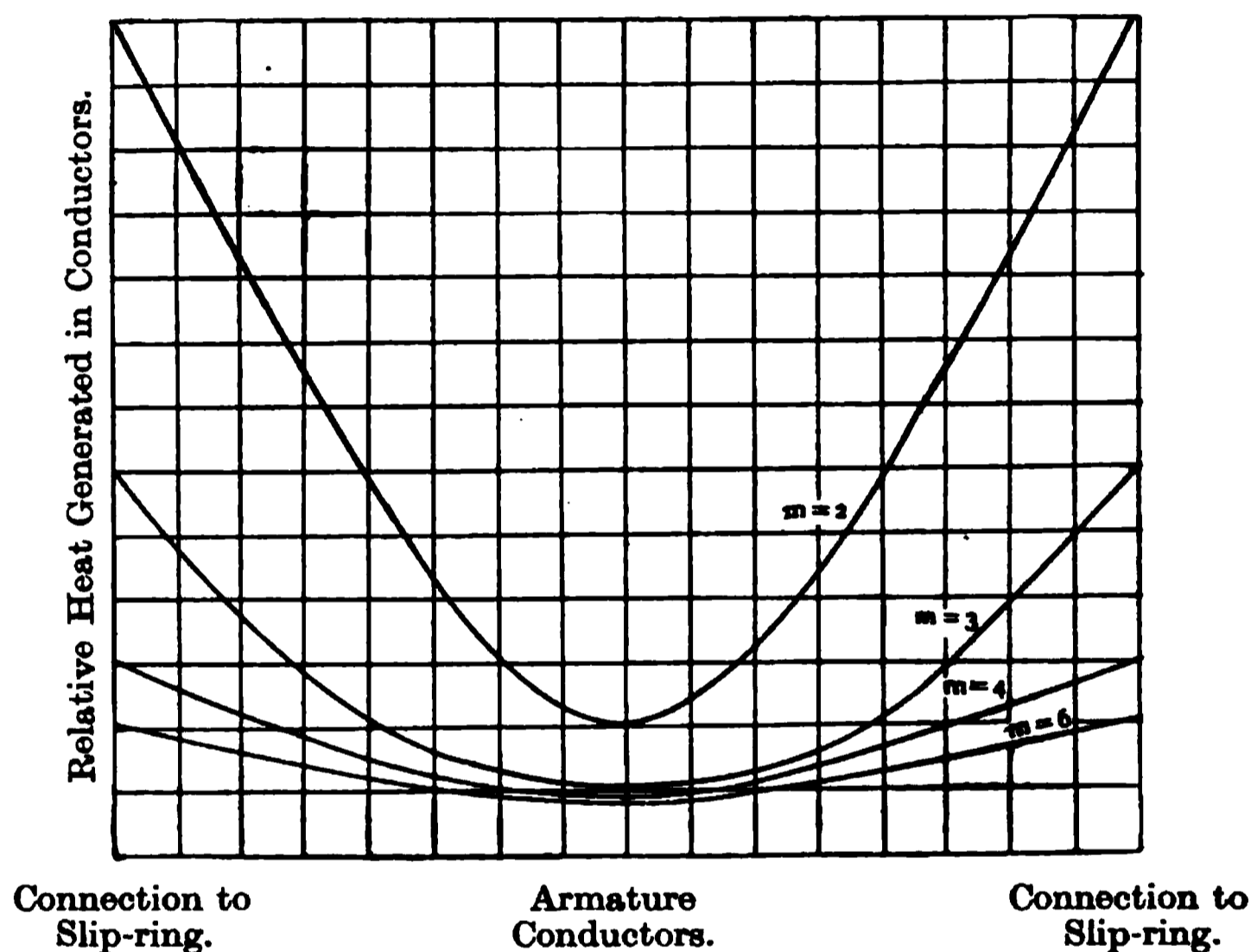


FIG. 492.—Variation of Heating of Armature Conductors with Number of Slip-rings (m), and Position of Conductors Relative to Tappings.

power-factor will alter the magnitude of the voltage at the slip-rings, due to the variation in the phase of the voltage drop in the reactance coils.

Thus, in Fig. 493, the E.M.F. induced in the secondary winding of the transformer (which is assumed to be constant) is represented by OE , while the current in this winding is represented by OI . The voltage drop due to the reactance in the circuit is represented by OX —lagging 90 degrees behind OI —and the voltage at the slip-rings is given by OV . The variation of OV , with the variation in the magnitude and phase of OI , is apparent from an inspection of the diagrams.

Adjustment of the compounding effect can be obtained by shunting the series winding, although it is not the practice to alter this adjustment after the machine has been installed.

In cases where regulation of the voltage is required without altering the power-factor, it is necessary to adopt other methods, such as an

induction regulator, a synchronous booster (see Fig. 499), or divided poles.*

Operating Features of Rotary Converters.—On account of the

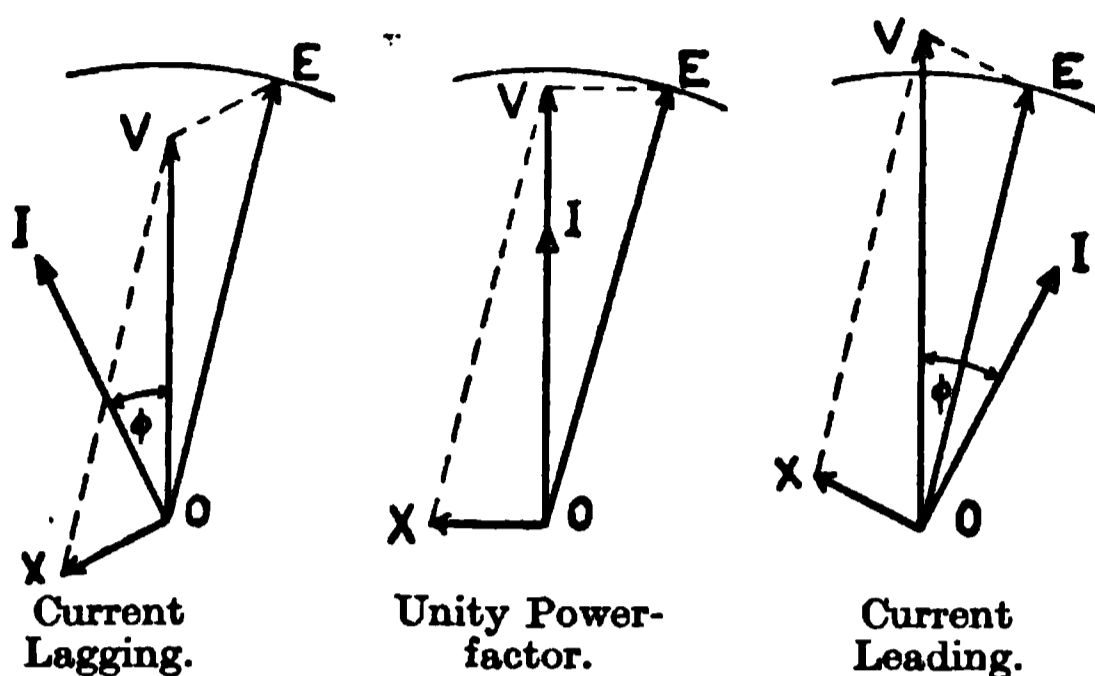


FIG. 493.—Vector Diagrams illustrating “Compounding” of Rotary Converter.

small resultant current in the armature conductors of a rotary converter, the armature reaction will be low, and the machine can be operated with the brushes in the neutral position. Commutation will therefore be

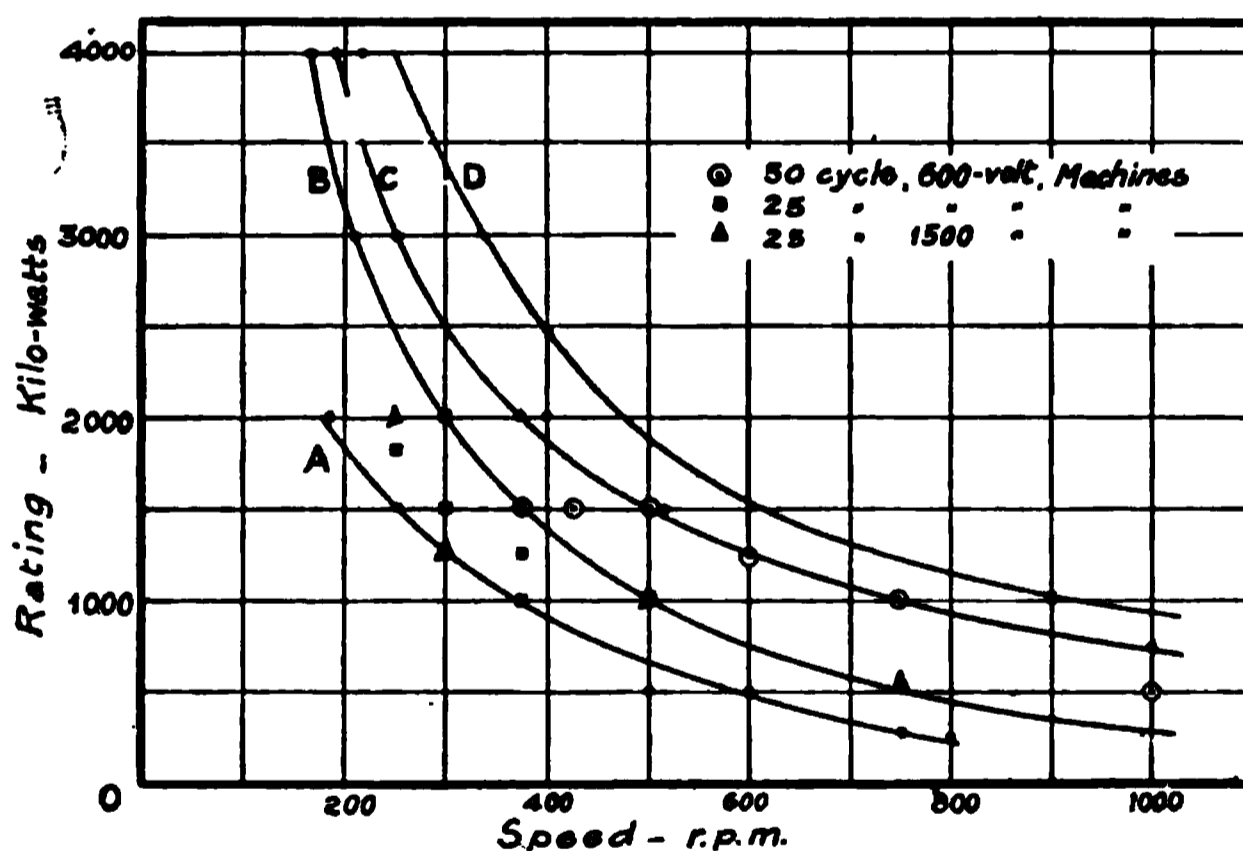


FIG. 494.—Relation between Speed and Output of Rotary Converters. A, 25-cycle non-commutating-pole machines; B, 25-cycle commutating-pole machines; C, D, 50- and 60-cycle commutating-pole machines. NOTE.—Points thus [.] refer to American machines, other points refer to British machines.

affected principally by the reactance voltage produced in the coils undergoing commutation.

The provision of commutating poles, however, will enable satisfactory

* For details of these methods see *Transactions of the American Institute of Electrical Engineers*, vol. 27, pp. 181, 191, 959. See also *Alternating Current Machinery*, p. 442.

commutation to be obtained at heavy overloads with higher values of the "specific electric loading" (i.e. the ampere-turns per unit length of armature periphery) than would be permissible in machines without commutating poles. Moreover, machines with commutating poles can be designed for much larger outputs per pole than machines without

FIG. 495.—Portion of Frame of B.T.-H. Rotary Converter, showing Pole-face Damping Winding and Commutating Poles.

commutating poles. For instance, in some of the Chicago sub-stations a number of 2000 kw., 16-pole, rotary converters (without commutating poles) have recently been replaced by 4000 kw., 18-pole, machines with commutating poles, the same foundations being used in each case. The 4000 kw. machines are rated at 4000 kw. continuously, 6000 kw. for two hours, and 12,000 kw. momentarily.

Commutating-pole rotary converters can also be designed for higher speeds and higher voltages than machines without commutating poles.

The increase in speed (which has been rendered possible by the intro-

duction of commutating poles) has enabled machines for operating on circuits of 50 and 60 frequency to be built in large sizes. For example, 60-cycle machines of the following ratings are in service in the United States: 2500 kw., 500 volts, 400 r.p.m.; * 1500 kw., 600 volts, 600 r.p.m.; 1000 kw., 600 volts, 900 r.p.m.; 300 kw., 750 volts, 1200 r.p.m.

The relation between the speed and rated output is shown better by the curves of Fig. 494. Curve A refers to 25-cycle machines (without commutating poles), built in 1908-9; curve B refers to 25-cycle machines

FIG. 496.—B.T.-H. 1500 kw. Rotary Converter with Starting Motor and Oscillator.

(with commutating poles) of recent manufacture; while curve D represents the latest achievement in 60-cycle machines.

The curves refer principally to machines of American manufacture,

* This machine has been described in the *Electric Journal* (vol. 11, p. 582) in an article, by Mr. J. L. McK Yardley, on "High Speed Rotary Converters" from which the following particulars are taken: The machine is rated at 5000 amperes, 500 volts, continuously, with a temperature rise of 35° C. (commutator 40° C.) the overload rating being 7500 amperes, 500 volts, for two hours. The peripheral speed of the armature is, approximately, 9400 ft. per minute, and that of the commutator is 5500 ft. per minute.

The guaranteed efficiencies, which were exceeded on test, are as follows:

Percentage of full load	. . . . . 50	75	100	125
Percentage efficiency	. . . . . 92.3	94.4	95.4	95.5

but points relating to machines of British manufacture are also shown on the curve sheet.

Modern rotary converters are practically free from surging or hunting, and are able to withstand large overloads without flashing over.* The elimination of hunting is obtained by the adoption of efficient damping devices in the pole shoes. The pole shoes of the main poles are laminated, and have a number of copper rods inserted through them near the pole face, the ends of the rods being expanded into copper end-plates or rings, thus forming practically a squirrel-cage winding. With commutating-pole machines the end-rings cannot be made continuous, since in this case the commutating pole would be surrounded by a closed circuit of

FIG. 497.—Alternating-current Side of B.T.-H. Rotary Converter.

low resistance, the effect of which would retard the growth of the commutating flux. An illustration of the damping system for a modern commutating-pole rotary converter is given in Fig. 495.

Examples of Modern Rotary Converters.—Fig. 496 illustrates a six-phase rotary converter (built by the British Thomson-Houston Co.) of the type which has recently been installed in a number of sub-stations on the London electric railways (including the London and South-Western Railway, the London and North-Western Railway, and the London

* The results of some flash-over tests with rotary converters are given in a paper by Mr. J. L. McK. Yardley on "The Use of Reactance with Synchronous Converters." See *Transactions of the American Institute of Electrical Engineers*, vol. 33, p. 1521. In the paper it is shown that a certain 60-cycle, 750-volt, rotary converter (without commutating poles) was able to commute a current of nearly ten times the normal full-load current, although the machine was not able to withstand the sudden switching-off of this current.

Underground Railways). The machine illustrated is compound wound for 600/630 volts, and is fitted with commutating poles. The starting motor is shown to the right of the magnet frame of the rotary converter, and is arranged for self-synchronising the latter, as described later.

FIG. 498.—Alternating-current Brush-gear for B.T.-H. Rotary Converter.

The projection on the pedestal bearing at the commutator end is a mechanical device * (called an **oscillator**) for oscillating the armature in a longitudinal direction. This device is fitted in order to reduce the tendency of the brushes to wear grooves in the commutator and slip-rings.

Fig. 497 is typical of the alternating-current side of a six-phase rotary converter without starting motor. The slip-rings, the alternating-current brush gear, the tapplings from the armature winding to the slip-rings, and the connections between the commutating-pole spools can be clearly seen.

The alternating-current brush gear is shown in detail in Fig. 498,

* An interesting article (by Mr. P. M. Lincoln) on the development of the oscillator will be found in *The Electric Journal*, vol. 12, p. 162.

from which it will be observed that the top-plate carrying the springs can be swung back so that the brushes can be easily removed, cleaned, or replaced.

The machine illustrated in Fig. 497 is equipped with a centrifugal speed-limiting device which is shown fitted to the shaft at the pedestal bearing. This device is arranged to trip the continuous-current circuit-breaker in the event of the speed exceeding the normal by 15 per cent. Under normal operating conditions the device is inoperative, since the speed is held to the normal value by the frequency of the supply circuit. If, however, the alternating-current circuit-breaker should open, while the machine is still connected to the continuous-current bus-bars, the

FIG. 499.—B.T.-H. Rotary Converter with Synchronous Booster and Field Break-up Switch.

speed may increase unduly, since in this case it depends only on the excitation and the bus-bar voltage.

Fig. 499 illustrates a rotary converter fitted with a synchronous booster for the purpose of regulating the voltage. The booster has the same number of poles as the converter, and is separately excited, the excitation being capable of adjustment between certain positive and negative values. The armature winding of the booster is connected in series with that of the converter, so that the voltage impressed on the latter will be given by (slip-ring voltage \pm voltage generated in booster winding). The variation of the continuous-current voltage can therefore be obtained with constant voltage at the slip-rings and constant (unity) power-factor. Machines of this type are used when a combined lighting and traction load have to be supplied from one sub-station.

In Fig. 499 a seven-bladed double-throw switch is shown fixed to the magnet frame of the rotary converter. This switch is connected

to the shunt field winding, so that the connections between individual spools may be broken, or the whole field winding may be reversed in relation to the brush leads (see Fig. 500). The switch is used (in the manner described below) when the machine is started up from the alternating-current side.

Methods of starting Rotary Converters.—The following methods of starting are available: (1) from the continuous-current side, by operating the machine as a continuous-current motor; (2) from the alternating-current side, by supplying the armature with reduced alternating voltage; (3) by the use of a separate starting motor; (4) by the use of a separate starting motor, of the induction type, connected in series with the slip-rings.

The first method requires a starting switch and rheostat, and involves

FIG. 500.—Connections for Six-phase Rotary Converter started from Alternating-current Side. Starting operations: (1) throw switches *A* and *B* "up"; (2) throw switch *A* "down"; (3) throw switch *B* "down."

synchronising the machine on the alternating-current side. When a number of machines in the same sub-station are equipped for this method of starting, a common starting panel is provided, and the main switches of each machine are of the double-throw type, so that any machine may be connected either to the main bus-bars or to the starting bus-bars.

The second method requires the provision of tapplings on the transformers, and a field break-up switch on the rotary converter (see Fig. 500), but it eliminates the synchronising of the machines. The connections for this method are shown in Fig. 500. It will be observed that the shunt field winding is divided into four sections, which are connected to the field break-up switch, so that when the latter is open the sections are disconnected from one another. This subdivision of the field winding is necessary at starting in order to avoid the production of high voltages in the field winding, due to transformer action from the armature winding.

At starting, the field switch is opened, and the slip-rings are con-

connected to the lowest-voltage tapping (usually one-third of normal voltage) of the transformers. The starting torque is obtained from the interaction of the armature current and the current induced in the damping grids in the pole faces, the action being similar in principle to that in a squirrel-cage induction motor. The field switch is closed as the machine reaches synchronous speed, and if the polarity is correct the starting switches are transferred to full voltage.

On account of the starting current being approximately twice the full-load current, the residual magnetism in the magnet frame and pole pieces is destroyed, and the polarity of the machine will depend on the polarity at the moment of reaching synchronism.

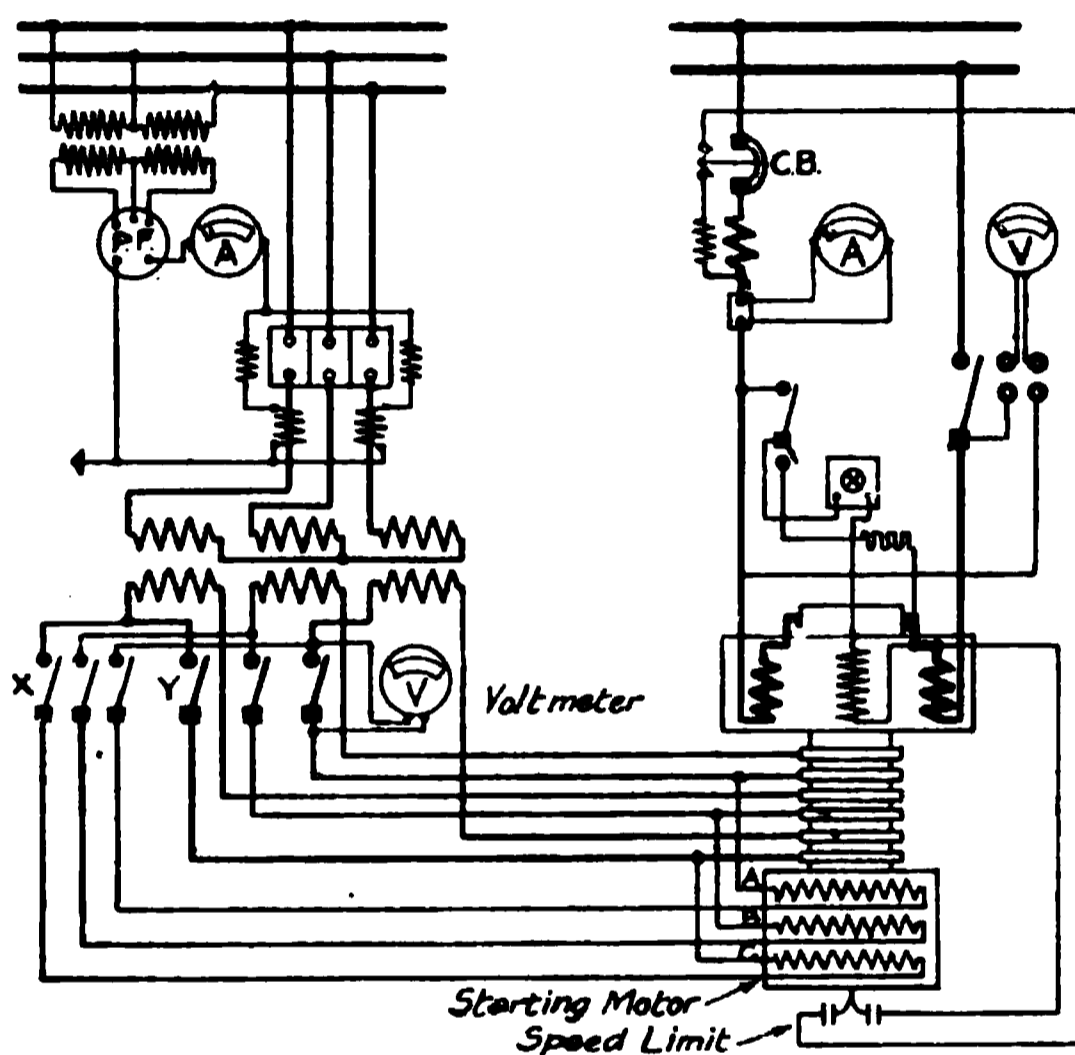


FIG. 501.—Connections for Six-phase Self-synchronising Rotary Converter started by Induction Motor. Starting operations: (1) close switch *X*; (2) close switch *Y*—after machine has synchronised—when voltmeter *V* indicates minimum voltage across starting motor.

If the machine builds-up with reversed polarity (as indicated by the voltmeter reading in the wrong direction), the armature must be slipped through a pole-pitch to obtain the correct polarity.* This process of “slipping a pole” is usually performed by means of a reversing switch in the field circuit. If, with the switch in the normal (“up”) position, the machine excites with reversed polarity, then the field switch is thrown into the bottom contacts, and changed over to the top contacts again when the machine starts to build-up in the right direction (as indicated by the voltmeter). When this method of starting is adopted with large commutating-pole machines, the brushes (with the exception of two brushes, of opposite polarity, for exciting purposes) must be raised from

* With the armature running in synchronism with the rotating field, the latter is stationary with respect to the field poles, and therefore the polarity of the field magnets can only be changed by slipping the armature through a pole-pitch.

the commutator since excessive sparking would otherwise occur, due to the presence of the unexcited commutating pole in the neutral zone. With small machines it is only necessary to short-circuit the commutating-pole winding.

The third method of starting—by the use of a separate motor—has been largely adopted in the rotary converter sub-stations in this country. The starting motor is usually of the induction type, and the number of poles on this machine must be a pair less than the number on the rotary converter. The rotary converter must be synchronised, and the adjustment of the speed for synchronising purposes is carried out either by regulating rheostats in the rotor circuit of the induction motor, or, when the latter has a squirrel-cage rotor, by loading the rotary converter on rheostats.

With modern machines this method of starting has been superseded by method (4) above, in which the stator windings of the induction motor are connected in series with the armature of the rotary converter, as indicated in Fig. 501. The starting motor is provided with a squirrel-cage rotor of high resistance, and is wound for a fewer number of poles than the rotary converter, as in the preceding method. At starting, the full secondary voltage of the transformers is switched on to the combination, and the high impedance of the starting motor limits the current in the armature of the rotary converter to about 30 per cent. of the full load current, which is insufficient to destroy the residual magnetism. The machine reaches synchronous speed in about 40 seconds, and, with the field rheostat properly adjusted, *automatically synchronises itself*. The induction motor is short-circuited when the voltage across its terminals is a minimum, which condition can be obtained, after the rotary converter has synchronised, by adjusting the field rheostat.*

With this method of starting there is no necessity for opening the field circuit, as the machine will always build-up with the correct polarity. Moreover, the whole process of starting is much simpler than that of the preceding methods.

Converting Machinery for High-voltage Continuous-current Railways.—In cases where continuous current at voltages greater than 750 volts is required, the choice of the converting plant will be influenced by the frequency of the alternating-current supply. When the supply is at 25 frequency, a single rotary converter may be used for voltages up to 1500 volts,† and two machines may be connected in series for higher voltages (up to 3000 volts). When the supply is at 60 frequency, however, it is necessary to use two (600 or 750 volt) machines,‡ connected in series, for 1200 or 1500 volts, and for higher voltages motor-generators must be adopted.

A typical motor-generator set (built by the General Electric Co.,

* For further particulars of self-synchronising (induction motor started) rotary converters see *Journal of the Institution of Electrical Engineers*, vol. 51, p. 62. Paper by Dr. E. Rosenberg on "Self-Synchronising Machines."

† A number of 25-cycle 1500-volt rotary converters, of 500, 1000, and 2000 kw. capacity, have recently been built by Messrs. Siemens Bros. Dynamo Works (Stafford) for the sub-stations of the Victorian Railways, Australia.

‡ The two machines may be mounted on a single bedplate with three bearings—the centre bearing being common to both machines—thus providing a compact set. See *Transactions of the American Institute of Electrical Engineers*, vol. 33, Plate 120, Fig. 10. Also *The Electric Journal*, vol. 12, p. 154.

Schenectady) for 2400-volt railway service is illustrated in Fig. 502. This set consists of a 60-cycle, 10-pole synchronous motor, direct-coupled to two 1200-volt, 4-pole, compound wound, continuous-current generators,

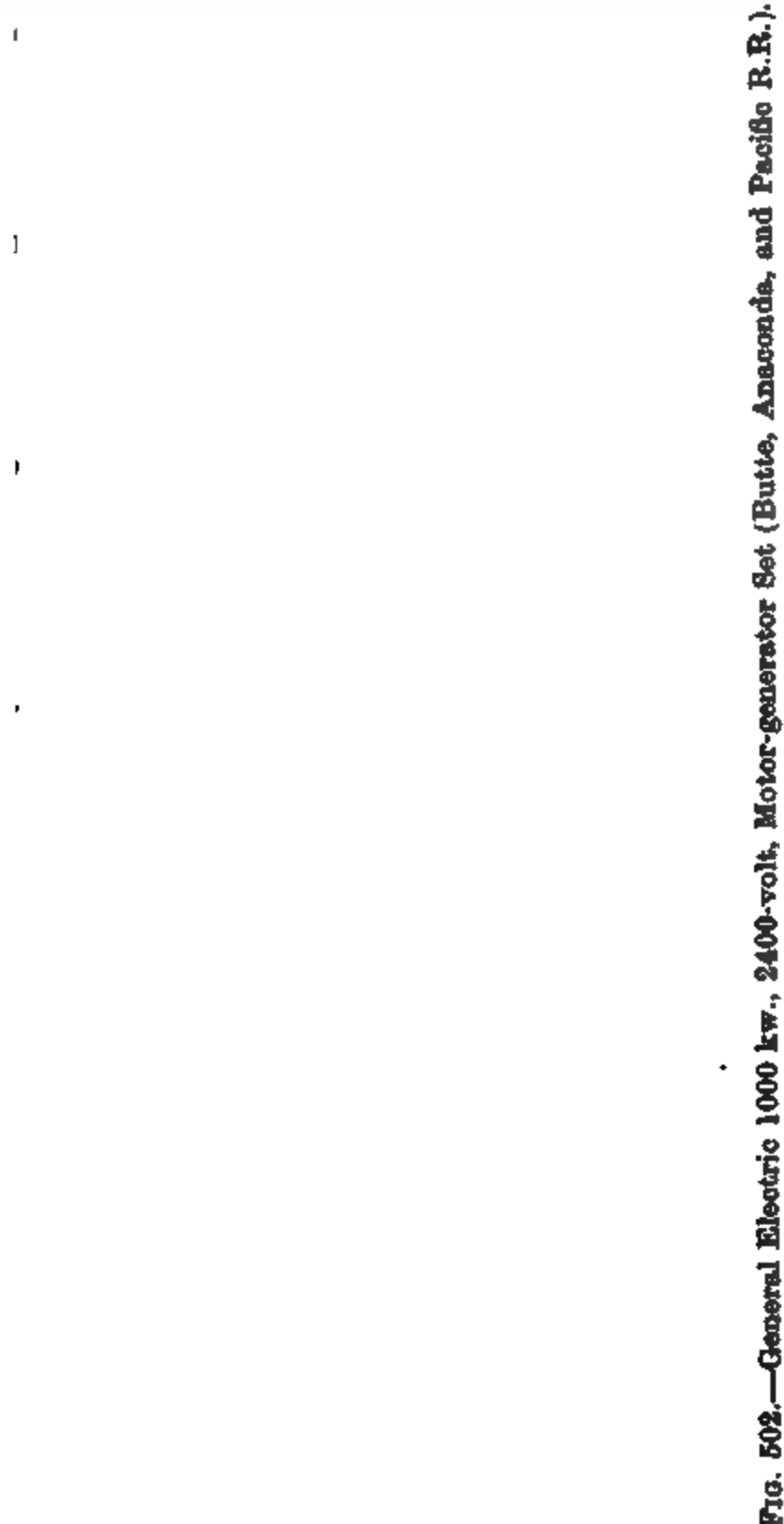


FIG. 502.—General Electric 1000 kw., 2400-volt, Motor-generator Set (Butte, Anaconda, and Pacific R.R.).

each generator being provided with commutating poles and compensating winding. The generators are connected in series, and the series windings are connected on the grounded side of the system, while the shunt field windings are separately excited from a 125-volt circuit. The

illustration (Fig. 502) refers to one of the sets in service on the Butte-Anaconda Railway, and these sets have been designed with a large overload capacity. For instance, each generator will carry 50 per cent. overload for two hours, and three times normal load momentarily. Similar sets, of large capacity, are being built for other high-voltage continuous-current railways.*

Capacity of the Sub-station Plant.—The load on a traction sub-station is of a totally different character from that on a sub-station supplying lighting and power. In the latter case, the load is practically steady; while the peak loads occur at definite times each day, and remain constant for a certain period. But in the former case the load is continually fluctuating, and a large peak load may occur quite unexpectedly, due to short-circuits or the “bunching” of cars or trains on the portion of the system being supplied from a particular sub-station. It is apparent that the individual units in the sub-station must be capable of operating under the latter conditions, but from an economical point of view the capacity of the plant installed should be no more than is sufficient to meet the average demand, with a reasonable allowance of spare machines for service in case of breakdowns or other contingencies. The overload capacity of the plant is therefore an important consideration, and this factor increases in importance as the number of sub-stations is reduced, assuming the external traffic to remain constant.

The size of the plant-unit and the number of units to be installed in each sub-station is decided from considerations of the traffic. Obviously the machines running under the various conditions of traffic should be, as far as possible, fully loaded. But the use of a number of machines of different sizes is to be avoided, since this results in a variety of spare parts (such as brushes, spare coils, &c.) being required, and does not facilitate the temporary interchange of machines between sub-stations (such as may be necessary in cases of breakdowns). Thus, on the larger traction systems in this country, we find that only a few sizes of plant are installed in the sub-stations. For example, on the Central London Railway one size (900 kw.) of rotary converter has been installed throughout, while on the London Underground Electric Railways—on which system nearly a hundred rotary converters are installed—the machines are of three sizes, viz. 800, 1200, and 1500 kw.

Again, the majority of the sub-stations on the London County Council Tramways (of which there are a total of 24) are provided with motor-generators of a uniform size, viz. 500 kw. Although the individual sets have been manufactured by several firms, the bedplates and foundation bolts are of one standard size.† The more recent sub-stations in the central districts of the tramway system have been equipped with rotary converters of 1500 kw. capacity.

Sub-station Plant additional to Converting Machinery.—When the converting machinery consists of rotary converters, static trans-

* High-voltage continuous-current generators, for voltages up to 5000 volts in a single machine, have been built in this country by Messrs. Dick, Kerr & Co., Preston. A 500-kw. motor-generator set, with a 3750-volt generator, has been installed by this firm in the sub-station supplying the experimental (Bury-Holcombe Brook) line of the Lancashire and Yorkshire Railway.

† See a paper by Mr. J. H. Rider on “The Electrical System of the London County Council Tramways” (*Journal of the Institution of Electrical Engineers*, vol. 43, p. 235).

formers are required for the purpose of supplying a suitable voltage to the slip-rings. The transformers may be of the self-cooled type, or of the forced ventilated (air-blast) type. In the latter case auxiliary plant—e.g. motor-driven blowers—is required, while air ducts must be provided for the conveyance of the air from the blowers to the respective transformers. In some cases air filters will also be required.

Of the two types of transformers, the air-blast type is the lighter, and occupies the smaller space; but these advantages are counter-balanced by the disadvantages of the additional ventilating plant required with these transformers.

The transformers may be located on the same floor as the rotary converters, in a basement, or on a gallery, the latter location being generally adopted for air-blast transformers. Examples of sub-stations showing the location of the plant, &c., are given below.

In sub-stations supplying overhead tramways it may be necessary to instal **negative boosters**, the purpose of which is to maintain the voltage drop in the track rails within the Board of Trade limit (see Board of Trade Regulations, p. 635). The uses of negative boosters are discussed in Chapter XXVI.

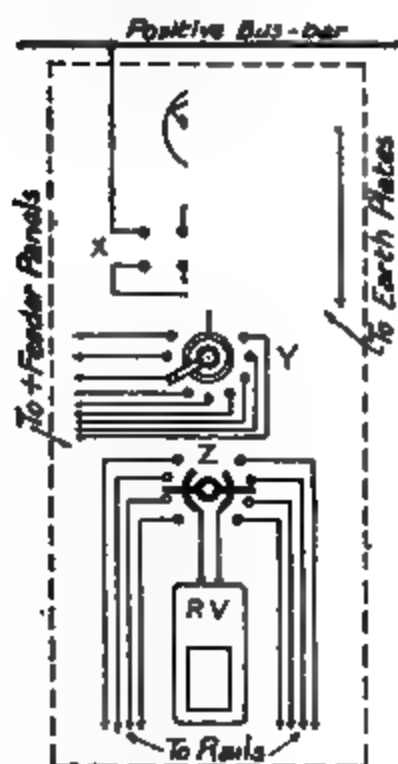


FIG. 503.—Diagram of Connections for Board of Trade Panel.

Switchgear.—The switchgear required in a sub-station containing converting machinery will include (a) switchgear for dealing with the high-tension incoming and interconnecting feeders, (b) switchgear for controlling the converting machinery, (c) switchgear for controlling the distribution of the continuous current to the low-tension system. Since the switchgear for items (a) and (b) does not present any special features for traction service, we shall only consider the switchgear required for the low-tension distributing system.

In the case of sub-stations supplying **overhead tramways**, this switchgear will include (1) line, or positive, feeder panels; (2) track, or negative, feeder panels; (3) Board of Trade panel for testing purposes.

The line (positive) feeder panels are generally equipped with an automatic overload circuit-breaker, an ammeter, and a single-pole switch.

The equipment of the track (negative) feeder panels varies according to circumstances. In cases where negative boosters and a number of track feeders are installed, switchgear is usually provided in the form of vertical and horizontal bars with connecting plugs, to enable any track feeder to be connected to any booster (see Fig. 508). The line feeders and the (series) field windings of the boosters are arranged in a similar manner, so that the line feeder corresponding to a given track feeder may be connected in series with the field winding of the booster to which the track feeder is connected.

The **Board of Trade panel** is equipped with the necessary instruments and switches to comply with the Board of Trade Regulations (see Appendix I, p. 633). The instruments comprise (1) a recording volt-

meter—range 0–10 volts ; (2) a double-range indicating ammeter—ranges 0–0·05 amperes, 0–5 amperes.

The former instrument is required for the purpose of recording the potential difference between certain points in the rails (see Regulations, p. 635), while the latter instrument is required for the purpose of measuring the leakage current (see Regulations, p. 635) and for testing the conductivity between the earth plates (see Regulations, p. 634).

The connection of the instruments to the various circuits is accomplished by means of multi-contact and change-over switches, the general scheme of connections being shown in Fig. 503. It should be observed that, when the change-over switch *X* is thrown over to the right, the higher (0–5 ampere) range of the ammeter is connected in series with a four-volt storage battery to one of the earth plates, while the other earth plate is connected to the other pole of the battery. When the switch is thrown over to the left, the lower (0–0·05 ampere) range of the ammeter is connected to the multi-contact switch *Y*, which is connected to the line feeders.

In some cases it is necessary to provide a recording ammeter—range 0–20 amperes—for the purpose of complying with Regulation 5 (p. 634), which refers to the current returning to the negative bus-bar *via* the earth plates. In recent installations the alternative instrument—viz. a maximum demand indicator—allowed by the Board of Trade is generally adopted and is located in the feeder pillars (see p. 582).

The switchgear required for **conduit tramways** differs, in many respects, from that for overhead tramways. In the first place, for each positive feeder a corresponding negative feeder is provided, the positive and negative feeders being connected respectively to the two conductor rails in the conduit.

Secondly, provision must be made for detecting the *nature* of faults, which may occur on the cars or in the conduits. Each feeder panel is therefore equipped with a double-pole reversing switch, two ammeters, and a single-pole overload circuit-breaker, as represented in Fig. 504.

On the London County Council tramway system the switches on the conduit feeder panels are of special construction, the top and bottom main contacts being fitted with auxiliary contacts (see Fig. 505), which are insulated from the main contacts and are connected to a special pair of bus-bars (called the testing bus-bars). The testing bus-bars may be

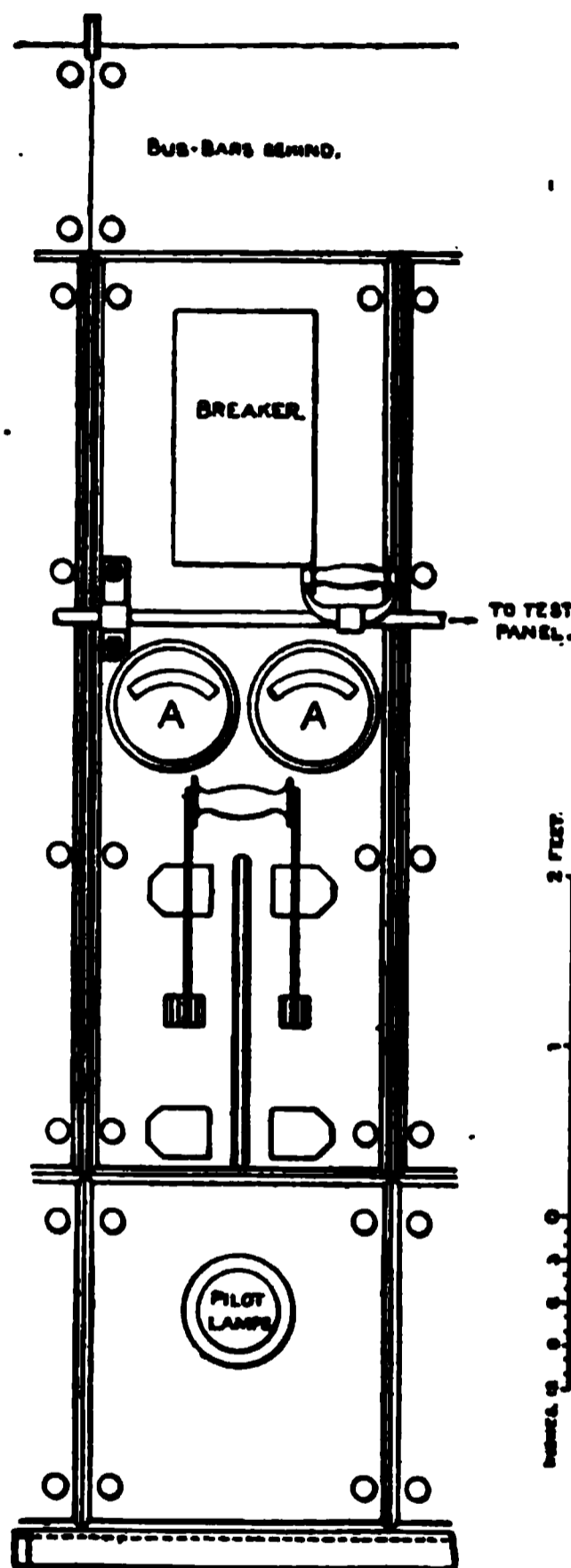


FIG. 504.—Feeder Panel for Conduit Tramways.

connected to the main bus-bars through metallic resistances (having a total resistance of approximately 5 ohms), circuit-breakers, and ammeters (see Fig. 506), the instruments and circuit-breakers being located on a special panel—the test panel—fixed at right angles to the feeder panels. This test panel is also equipped with the instruments for carrying out the Board of Trade tests (see Regulations, p. 636). The circuit-breakers on the test panel are operated from a shaft running the length

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SLATE BARRIER.

FIG. 505.—Detail of Change-over Feeder Switch.

of the feeder panels, this shaft being shown in Fig. 504, just above the ammeters.

The negative bus-bar of the sub-station is connected to earth through a recording ammeter and a liquid rheostat (see Fig. 506), the latter being usually kept at about 1 ohm.

The upper portion of the test panel carries four groups of incandescent lamps, the upper groups being connected between the testing bus-bars and earth, and the lower groups being connected between the main bus-bars and earth.

On account of the negative bus-bar being earthed, all positive faults are shown by the opening of the circuit-breaker on the feeder panel, and by the change in the brightness of the lamps on the test panel.

In the event of the circuit-breaker on the feeder panel opening (due to a positive fault, or a fault between the conductor rails), the switch on the feeder panel is withdrawn into the auxiliary contacts, and the circuit-breakers on the test panel are closed. The magnitude of the fault is then shown by the indications of the instruments on the test panel. If the fault should be a bad one, the switch on the feeder panel is thrown to the lower auxiliary contacts, which enables the character of the fault to be ascertained. For instance, a short-circuit between the conductor rails would be shown as a bad fault in each position of the feeder switch, but a positive fault would be shown as "clear" when the switch was placed in the lower auxiliary contacts.

A short-circuit between the conductor rails would, of course, necessitate a visit to the faulty section of the track, but with a positive fault the service can be maintained by temporarily reversing the polarity of the conductor rails of the section on which the fault has occurred (e.g. by placing the feeder switch in the lower main contacts).

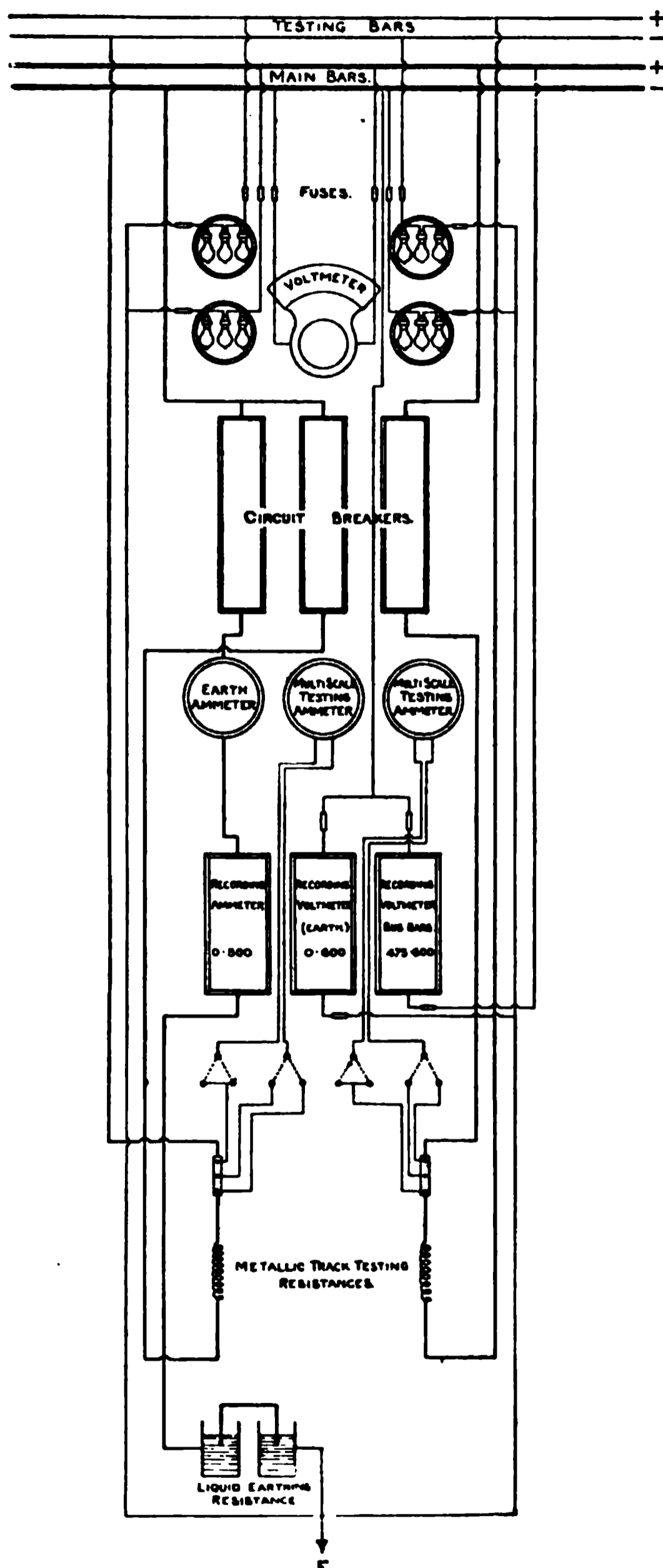


FIG. 506.—Connections of Test Panel (London County Council Conduit Tramways).

(e.g. by placing the feeder switch in the lower main contacts).

In these circumstances the resistance in the negative bus-bar earth connection would be increased, so as to limit the current returning to the station *via* earth.

Negative faults are shown by the difference in the indications of the two ammeters on the feeder panels. In order to locate a car which has a negative fault, the polarity of one section of the track is reversed, and as the car enters that section the fault is transferred to the positive side, thereby opening the feeder circuit-breaker.

The leakage tests (see Regulations, p. 636) are carried out by placing the feeder switches—one at a time—in the auxiliary contacts, and noting the indications on the ammeters on the test panel, the two multi-scale ammeters (shown in Fig. 506) being provided with a suitable range for this purpose.

The switchgear for sub-stations supplying **continuous-current railways** usually follows the general lines of that (outlined above) for overhead tramways, except that, as no negative boosters are adopted, only panels for the conductor-rail feeders are required. In the case of railways on which positive and negative conductor rails are adopted, the feeder panels for each section are equipped with two single-pole circuit-breakers, two single-pole switches, and an ammeter.

In the case of railways in which the track rails are used as the return, the positive feeder panels are equipped with a single-pole circuit-breaker, a switch, and an ammeter. The negative feeders from the track rails are generally connected directly to the negative bus-bar. A Board of Trade panel (with a recording voltmeter for the rail drop) is required.

EXAMPLES OF TRACTION SUB-STATIONS

A few illustrations of typical tramway and railway sub-stations are given in Figs. 507 to 518.

Fig. 507 refers to one of the sub-stations of the **Leeds Tramways**. The sub-station is equipped with three 325 kw., three-phase, 525/575 volt, 25-cycle rotary converters (with ball bearings), and one motor-driven negative booster. The transformers are of the three-phase oil-cooled type, and are located in the basement. The sub-station floor above the transformers consists of chequer plates, so that the transformers can be readily handled by the crane.

The rotary converters are arranged for starting from the alternating-current side, the starting panels being located immediately in front of each rotary converter, as shown in Fig. 507. The two double-pole double-throw switches on the upper portion of the starting panel connect two of the slip-rings to tappings on two of the transformers, the third slip-ring being connected directly to the transformers. Below these switches is the field switch, and on the sub-panel is fitted a single-pole switch for short-circuiting the series field winding. The small instrument above the starting switches is a polarity indicator.

Fig. 508 illustrates a sub-station of the **Glasgow Tramways**. In this sub-station the transformers and high-tension alternating-current switchgear are located in an adjoining room, the oil-switches being electrically controlled from a desk-type control board located in the centre of the sub-station. Each of the rotary converters is provided with a starting motor and a negative booster.

The continuous-current switchgear is shown on the right-hand side of the sub-station. In the foreground there are five panels controlling the line (positive) feeders, three feeders being controlled by each panel. The switches are of the double-throw pattern. The lower contacts of these switches are connected to the vertical plug-bars on the sub-panels, and on the back of the board there are four horizontal bars which are each connected, through suitable switches, to one end of the field windings of the boosters, the other ends of the field windings being connected to the positive bus-bar through suitable switches. The upper contacts of the feeder switches are connected directly to the positive bus-bar.

FIG. 507.—Interior of Sub-station—Leeds Tramways—showing Westinghouse Rotary Converters and Starting Panels.

Thus any feeder or a group of feeders may be connected so as to excite any of the negative boosters.

The switches controlling the boosters are adjacent to the feeder panels. The upper row of switches control the field windings, and the lower row of switches control the armatures, one switch connecting the positive brush to the negative bus-bar, and the other switch connecting the negative brush to the vertical plug-bar on the sub-panel. The horizontal plug-bars extend along the back of the board to the track-feeder panels, which are located at the far end of the board, adjacent to the Board of Trade panel. Each track feeder is connected, through a switch and an ammeter, to a vertical plug-bar, so that any track feeder may be connected to any booster. Between the booster panels and the track-feeder panels are located the panels controlling the continuous-current sides of the rotary converters, these panels being distinguished by the field rheostats on the sub-panels.

FIG. 508.—Interior of Partick Sub-station (Glasgow Tramways).

FIG. 509.—Interior of Sub-station on District Railway, London.

**FIG. 510.—Westinghouse Air-blast Transformers
in Sub-station of District Railway.**

Fig. 509 illustrates a typical sub-station of the **London Underground Electric Railways** (Metropolitan District Railway). In these sub-stations the rotary converters are provided with starting motors, while the transformers are of the air-blast type, and are mounted on a gallery above the switchboard (see Fig. 510), the ventilating trunk being carried immediately under the gallery. The high-tension oil-switches for the transformers and feeders are located in brick compartments behind the switchboard, the switches being mechanically operated by levers of the railway-signal type.

FIG. 511.—Interior of Sub-station on Metropolitan Railway, London.

The low-tension switchboard is located on the same floor as the rotary converters. The panels in the foreground of Fig. 509 control the positive and negative conductor-rail feeders. Adjacent to these are the (three) panels controlling the continuous-current sides of the rotary converters, these panels being distinguished by the field rheostats on the sub-panels. Next follow the panels controlling the low-tension alternating-current sides of the rotary converters, with the switches controlling the starting motors of the rotary converters located on the sub-panels. The panels at the far end of the switchboard comprise an instrument panel for the high-tension alternating-current feeders, and a panel for controlling the lighting circuits (which are supplied with alternating current).

The equaliser switches for the rotary converters are mounted on pedestals located near the machines.

A sub-station on the **Metropolitan Railway** (London) is illustrated in Fig. 511. In this sub-station the transformers are of the oil-cooled single-phase type, and are located in a specially ventilated chamber adjacent to the rotary converters. The ceiling of this chamber forms the floor of the switchboard gallery, and manholes are provided so that the transformers can be handled by a crane. The oil-switches are mechanically operated by levers, and are located in a chamber at the back of the transformers. With the exception of the transformers and their location, the equipment of these sub-stations is similar to that of the majority of the sub-stations on the Metropolitan District Railway.

Views of two of the sub-stations on the **London and South-Western**

FIG. 513.—Interior of Clapham Junction Sub-station (London and South-Western Railway), showing Rotary Converters and Transformers.

Railway are shown in Figs. 512 and 513, the former illustration being representative of the majority of the sub-stations. The rotary converters are of the six-phase self-synchronising type, and are rated at 1500 kw., 600/630 volts, 300 r.p.m., 25 cycles. Each machine is supplied through three single-phase oil-cooled transformers, which are located on a raised portion of the floor adjacent to the machines (see Fig. 513). The low-tension connections on both sides of the machines consist of bare copper strip.

The switchboard for controlling the machines and the conductor-rail feeders is shown in Fig. 514, while the high-tension switchgear is shown in Fig. 515. Referring to Fig. 514, the first group of four panels control the conductor rail (positive) feeders, and the remaining three panels control the rotary converters. Due to these machines being of the self-synchronising type, the alternating-current switchgear controlling them only consists of (1) remote controlled oil-switches for the high-tension side of the transformers, (2) short-circuiting switches for the starting

FIG. 514.—Switchboard for Controlling Rotary Converters and Conductor-rail Feeders (London and South-Western Railway).

motors. The short-circuiting switches are located on the machines (see Fig. 513), while the levers for operating the oil-switches are mounted on the switchboard with the continuous-current switchgear. The instruments on each machine panel include a main continuous-current

FIG. 515.—Arrangement of High-tension Switchgear in Typical Sub-station (London and South-Western Railway).

ammeter, a field ammeter, an alternating-current ammeter, and a power-factor indicator.

The oil-switches controlling the transformers, together with those controlling the high-tension feeders, are located in compartments of moulded stone arranged on a gallery, as shown in Fig. 515. In this illustration the bus-bar compartments are also shown.

The equipment of **sub-stations supplying high-voltage continuous-current railways** differs from that of the above sub-stations principally in the continuous-current switchboard, and, in some cases, the converting plant. On the **Lancashire and Yorkshire Railway, Manchester-Bury**

FIG. 516.—Interior of Typical Sub-station, Lancashire and Yorkshire Railway—1200-volt (Manchester-Bury) Section.

FIG. 517.—B.T.-H. Continuous-current, 1200-volt Switchboard in Sub-station on Lancashire and Yorkshire Railway.

(1200-volt) section, the converting machinery consists of six-phase self-synchronising rotary converters rated at 1000/1250 kw., 1200 volts, 300 r.p.m., 25 cycles. Each machine is supplied through three single-

FIG. 518.—G. E. 2400-volt, Continuous-current Switchboard in Sub-station on Butte, Anaconda, and Pacific Railway.

phase oil-cooled transformers, which are located adjacent to the machines, on the same floor level.

Views of a typical sub-station on this railway are shown in Figs. 516, 517.

The continuous-current switchboard (built by the British Thomson-

Houston Co.) is designed so that all 1200-volt apparatus occupies the upper portion of the board, the switches and circuit-breakers being operated by means of insulated levers.

A view of a **2400-volt switchboard** manufactured by the General Electric Co., Schenectady, is shown in Fig. 518. In this view the switches, circuit-breakers, and instruments are shown in detail. The four panels on the right control 2400-volt feeders for the trolley-wires. Each of these panels is equipped with an ammeter (with a shielded case), a single-pole switch, and an automatic overload circuit-breaker. The switches and circuit-breakers are located at the top of the board on separate panels, and are operated by means of insulated levers. The circuit-breakers are provided with a magnetic blow-out and special arc chute.

The panels adjacent to the feeder panels control the continuous-current sides of two synchronous motor-generator sets, one of the sets being illustrated in Fig. 502. The remaining panels control the synchronous motors of these sets and the exciter, while the extreme end panel is equipped with integrating wattmeters and a Tirrill automatic voltage regulator.

APPENDIX I

REGULATIONS MADE BY THE BOARD OF TRADE UNDER THE PROVISIONS OF SPECIAL TRAMWAYS ACTS OR LIGHT RAILWAY ORDERS AUTHORISING LINES ON PUBLIC ROADS ; FOR REGULATING THE USE OF ELECTRICAL POWER ; FOR PREVENTING FUSION OR INJURIOUS ELECTROLYTIC ACTION OF OR ON GAS OR WATER PIPES OR OTHER METALLIC PIPES, STRUCTURES, OR SUBSTANCES ; AND FOR MINIMISING AS FAR AS IS REASONABLY PRACTICABLE INJURIOUS INTERFERENCE WITH THE ELECTRIC WIRES, LINES, AND APPARATUS OF PARTIES OTHER THAN THE COMPANY, AND THE CURRENTS THEREIN, WHETHER SUCH LINES DO OR DO NOT USE THE EARTH AS A RETURN.

First made, March 1894. Revised, April 1903.

Further revised, September 1912.

Definitions

In the following regulations—

The expression “energy” means electrical energy.

The expression “generator” means the dynamo or dynamos or other electrical apparatus used for the generation of energy.

The expression “motor” means any electric motor carried on a car and used for the conversion of energy.

The expression “pipe” means any gas or water pipe or other metallic pipe, structure, or substance.

The expression “wire” means any wire or apparatus used for telegraphic, telephonic, electrical signalling, or other similar purposes.

The expression “current” means an electric current exceeding one-thousandth part of one ampere.

The expression “the Company” has the same meaning as in the Tramways Act [Light Railways Order].

Regulations

1. Any dynamo used as a generator shall be of such pattern and construction as to be capable of producing a continuous current without appreciable pulsation.*

2. One of the two conductors used for transmitting energy from the generator to the motors shall be in every case insulated from earth, and is hereinafter referred to as the “line” ; the other may be insulated throughout, or may be uninsulated in such parts and to such extent as is provided in the following regulations, and is hereinafter referred to as the “return.”

3. Where any rails on which cars run or any conductors laid between or within three feet of such rails form any part of a return, such part may be uninsulated. All other returns or parts of a return shall be insulated, unless

* The Board of Trade will be prepared to consider the issue of regulations for the use of alternating currents for electrical traction on application.

of such sectional area as will reduce the difference of potential between the ends of the uninsulated portion of the return below the limit laid down in Regulation 7.

4. When any uninsulated conductor laid between or within three feet of the rails forms any part of a return, it shall be electrically connected to the rails at distances apart not exceeding 100 feet by means of copper strips having a sectional area of at least one-sixteenth of a square inch, or by other means of equal conductivity.

5. (a) When any part of a return is uninsulated it shall be connected with the negative terminal of the generator, and in such case the negative terminal of the generator shall also be directly connected, through the current-indicator hereinafter mentioned, to two separate earth connections which shall be placed not less than 20 yards apart.

(b) The earth connections referred to in this regulation shall be constructed, laid, and maintained so as to secure electrical contact with the general mass of earth, and so that, if possible, an electro-motive force, not exceeding four volts, shall suffice to produce a current of at least two amperes from one earth connection to the other through the earth, and a test shall be made once in every month to ascertain whether this requirement is complied with.

(c) Provided that in place of such two earth connections the Company may make one connection to a main for water supply of not less than three inches internal diameter, with the consent of the owner thereof and of the person supplying the water, and provided that where, from the nature of the soil or for other reasons, the Company can show to the satisfaction of the Board of Trade that the earth connections herein specified cannot be constructed and maintained without undue expense, the provisions of this regulation shall not apply.

(d) No portion of either earth connection shall be placed within six feet of any pipe except a main for water supply of not less than three inches internal diameter which is metallically connected to the earth connections with the consents hereinbefore specified.

(e) When the generator is at a considerable distance from the tramway the uninsulated return shall be connected to the negative terminal of the generator by means of one or more insulated return conductors, and the generator shall have no other connection with earth; and in such case the end of each insulated return connected with the uninsulated return shall be connected also through a current indicator to two separate earth connections, or with the necessary consents to a main for water supply, or with the like consents to both in the manner prescribed in this regulation.

(f) The current indicator may consist of an indicator at the generating station connected by insulated wires to the terminals of a resistance interposed between the return and the earth connection or connections, or it may consist of a suitable low-resistance maximum demand indicator. The said resistance, or the resistance of the maximum demand indicator, shall be such that the maximum current laid down in Regulation 6 (i) shall produce a difference of potential not exceeding one volt between the terminals. The indicator shall be so constructed as to indicate correctly the current passing through the resistance when connected to the terminals by the insulated wires before-mentioned.

6. When the return is partly or entirely uninsulated the Company shall in the construction and maintenance of the tramway (a) so separate the uninsulated return from the general mass of earth, and from any pipe in the vicinity; (b) so connect together the several lengths of the rails; (c) adopt such means for reducing the difference, produced by the current, between the potential of the uninsulated return at any one point and the potential of the uninsulated return at any other point; and (d) so maintain the efficiency of the earth connections specified in the preceding regulations as to fulfil the following conditions, viz. :—

(i) That the current passing from the earth connections through the indicator to the generator or through the resistance to the insu-

lated return shall not at any time exceed either two amperes per mile of single tramway line or five per cent. of the total current output of the station.

- (ii) That if at any time and at any place a test be made by connecting a galvanometer or other current-indicator to the uninsulated return and to any pipe in the vicinity, it shall always be possible to reverse the direction of any current indicated by interposing a battery of three Leclanché cells connected in series if the direction of the current is from the return to the pipe, or by interposing one Leclanché cell if the direction of the current is from the pipe to the return.

The owner of any such pipe may require the Company to permit him at reasonable times and intervals to ascertain by test that the conditions specified in (ii) are complied with as regards his pipe.

7. When the return is partly or entirely uninsulated a continuous record shall be kept by the Company of the difference of potential during the working of the tramway between points on the uninsulated return. If at any time such difference of potential between any two points exceeds the limit of seven volts, the Company shall take immediate steps to reduce it below that limit.

8. Every electrical connection with any pipe shall be so arranged as to admit of easy examination, and shall be tested by the Company at least once in every three months.

9. The insulation of the line and of the return when insulated, and of all feeders and other conductors, shall be so maintained that the leakage current shall not exceed one hundredth of an ampere per mile of tramway. The leakage current shall be ascertained not less frequently than once in every week before or after the hours of running when the line is fully charged. If at any time it should be found that the leakage current exceeds one-half of an ampere per mile of tramway the leak shall be localised and removed as soon as practicable, and the running of the cars shall be stopped unless the leak is localised and removed within 24 hours. Provided that where both line and return are placed within a conduit this regulation shall not apply.

10. The insulation resistance of all continuously insulated cables used for lines, for insulated returns, for feeders, or for other purposes, and laid below the surface of the ground, shall not be permitted to fall below the equivalent of 10 megohms for a length of one mile. A test of the insulation resistance of all such cables shall be made at least once in each month.

11. Any insulated return shall be placed parallel to and at a distance not exceeding three feet from the line when the line and return are both erected overhead, or eighteen inches when they are both laid underground.

12. In the disposition, connections, and working of feeders, the Company shall take all reasonable precautions to avoid injurious interference with any existing wires.

13. The Company shall so construct and maintain their system as to secure good contact between the motors and the line and return respectively.

14. The Company shall adopt the best means available to prevent the occurrence of undue sparking at the rubbing or rolling contacts in any place and in the construction and use of their generator and motors.

15. Where the line or return or both are laid in a conduit the following conditions shall be complied with in the construction and maintenance of such conduit :—

- (a) The conduit shall be so constructed as to admit of examination of and access to the conductors contained therein and their insulators and supports.
- (b) It shall be so constructed as to be readily cleared of accumulation of dust or other *dbris*, and no such accumulation shall be permitted to remain.
- (c) It shall be laid to such falls and so connected to sumps or other means of drainage, as to automatically clear itself of water without danger of the water reaching the level of the conductors.

- (d) If the conduit is formed of metal, all separate lengths shall be so jointed as to secure efficient metallic continuity for the passage of electric currents. Where the rails are used to form any part of the return they shall be electrically connected to the conduit by means of copper strips having a sectional area of at least one-sixteenth of a square inch, or other means of equal conductivity, at distances apart not exceeding 100 feet. Where the return is wholly insulated and contained within the conduit, the latter shall be connected to earth at the generating station or sub-station through a high-resistance galvanometer suitable for the indication of any contact or partial contact of either the line or the return with the conduit.
- (e) If the conduit is formed of any non-metallic material not being of high insulating quality and impervious to moisture throughout, the conductors shall be carried on insulators the supports for which shall be in metallic contact with one another throughout.
- (f) The negative conductor shall be connected with earth at the station by a voltmeter and may also be connected with earth at the generating station or sub-station by an adjustable resistance and current indicator. Neither conductor shall otherwise be permanently connected with earth.
- (g) The conductors shall be constructed in sections not exceeding one-half a mile in length, and in the event of a leak occurring on either conductor that conductor shall at once be connected with the negative pole of the dynamo, and shall remain so connected until the leak can be removed.
- (h) The leakage current shall be ascertained daily, before or after the hours of running, when the line is fully charged, and if at any time it shall be found to exceed one ampere per mile of tramway the leak shall be localised and removed as soon as practicable, and the running of the cars shall be stopped unless the leak is localised and removed within 24 hours.

16. The company shall, so far as may be applicable to their system of working, keep records as specified below. These records shall, if and when required, be forwarded for the information of the Board of Trade.

Number of cars running.

Number of miles of single tramway line.

Daily Records

Maximum working current.

Maximum working pressure.

Maximum current from the earth plates or water-pipe connections (*vide* Regulation 6 (i)) where the indicator is at the generating works

Fall of potential return (*vide* Regulation 7).

Leakage current (*vide* Regulation 15 (h)).

Weekly Records

Leakage current (*vide* Regulation 9).

Maximum current from the earth plates or water-pipe connections (*vide* Regulation 6 (i)) where a maximum demand indicator is used.

Monthly Records

Condition of earth connections (*vide* Regulation 5).

Minimum insulation resistance of insulated cables in megohms per mile (*vide* Regulation 10).

Quarterly Records

Conductance of joints to pipes (*vide* Regulation 8).

Occasional Records

Specimens of tests made under provisions of Regulation 6 (ii).

STATUTORY RULES AND ORDERS, 191 . No. .

TRAMWAY (OR LIGHT RAILWAY) *

REGULATIONS, DATED.....191 , MADE BY THE BOARD OF
TRADE AS REGARDS ELECTRICAL POWER (OVERHEAD TROLLEY SYSTEM)
ON THE.....TRAMWAYS

The Board of Trade, under and by virtue of the powers conferred upon them in this behalf, do hereby make the following regulations for securing to the public reasonable protection against danger in the exercise of the powers conferred by Parliament with respect to the use of electrical power on the overhead trolley system on all or any of the tramways on which the use of mechanical power has been authorised by the..... (hereinafter called "the tramways") :

And the Board of Trade do also hereby make the following byelaws with regard to the use of electrical power on all or any of such tramways.

Regulations

I Every motor carriage used on the tramways shall comply with the following requirements, that is to say :—

(a) It shall be fitted, if and when required by the Board of Trade, with an apparatus to indicate to the driver the speed at which it is running.

(b) The wheels shall be fitted with brake blocks, which can be applied by a screw or by other means, and there shall be in addition an adequate electric brake.

[NOTE.—Where for a considerable distance the gradients are 1 in 15 or steeper, the following will be added to this regulation :

"and a slipper brake or other track brake approved by the Board of Trade for use on the tramways."]

(c) It shall be conspicuously numbered inside and outside.

(d) It shall be fitted with a suitable lifeguard, and with a special bell or whistle to be sounded as a warning when necessary.

(e) It shall be so constructed as to enable the driver to command the fullest possible view of the road.

II. No trailer carriage shall be used on the tramways except in the case of the removal of a disabled carriage.

III. Every carriage used on the tramways shall be so constructed as to provide for the safety of passengers, and for their safe entrance to, exit from, and accommodation in such carriage.

IV. Every carriage on the tramways shall, during the period between one hour after sunset and one hour before sunrise or during fog, carry a lamp so constructed and placed as to exhibit a white light visible within a reasonable distance to the front, and every such carriage shall carry a lamp so constructed and placed as to exhibit a red light visible within a reasonable distance to the rear.

V. The speed at which the carriages shall be driven or propelled along the tramways shall not exceed the rate of..... :—

VI. The electrical pressure or difference of potential between the overhead conductors used in connexion with the working of the tramways and the earth, or between any two such conductors, shall in no case exceed 550 volts. The electrical energy supplied through feeders shall not be generated at or transformed to a pressure higher than 650 volts, except with the written consent of the Board of Trade, and subject to such regulations and conditions as they may prescribe.

VII. The overhead conductors used in connexion with the working of

* Laid along public roads.

the tramways shall be securely attached to supports, the intervals between which shall not, except with the approval of the Board of Trade, exceed 120 feet, and they shall be in no part at a less height from the surface of the street than 17 feet, except where they pass under railway bridges.

VIII. The overhead conductors shall be divided up into sections not exceeding (except with the special approval of the Board of Trade) one-half of a mile in length, between every two of which shall be inserted an emergency switch so enclosed as to be inaccessible to pedestrians.

IX. No part of any electric line shall be used for the transmission of more than 300,000 watts, except with the consent in writing of the Board of Trade, and efficient means shall be provided to prevent this limit being at any time exceeded.

X. Each separate insulator on the overhead conductors shall be tested not less frequently than once in a month, and any insulator found to be defective shall at once be removed and an efficient insulator substituted.

XI. All electrical conductors fixed upon the carriages in connexion with the trolley wheel shall be formed of flexible cables protected by india-rubber insulation of the highest quality, and additionally protected wherever they are adjacent to any metal so as to avoid risk of the metal becoming charged.

XII. The trolley standard of every double-decked carriage shall be electrically connected to the wheels of the carriage in such manner as either to prevent the possibility of this standard becoming electrically charged from any defect in the electrical conductors contained within it or give a continuous warning signal to the driver or conductor. No passenger shall be allowed to travel on the roof of a carriage as long as there is risk of electric shock.

XIII. An emergency cut-off switch shall be provided and fixed so as to be conveniently reached by the driver in case of any failure of action of the controller switch.

XIV. If and whenever telegraph or telephone wires, unprotected with a permanent insulating covering, cross above, or are liable to fall upon, or to be blown on to, the overhead conductors of the tramways, efficient guard wires shall be erected and maintained at all such places.

XV. Where any accident by explosion or fire, or any other accident of such kind as to have caused or to be likely to have caused loss of life or personal injury, has occurred in connexion with the electric working of the tramways, immediate notice thereof shall be given to the Board of Trade.

Penalty

NOTE.—The..... using electrical power on the tramways contrary to any of the above regulations is, for every such offence, subject to a penalty not exceeding £10; and also in the case of a continuing offence, to a further penalty not exceeding £5 for every day during which such offence continues after conviction thereof.

MODEL DESCRIPTION OF ELECTRICAL EQUIPMENT (ON THE OVERHEAD TROLLEY SYSTEM) OF TRAMWAYS OR LIGHT RAILWAYS LAID ON PUBLIC ROADS.

NOTE.—*This model should be retained for reference. It is intended to show the amount of detail required, and not to suggest actual details. A description should be drawn up following the model as closely as circumstances permit.*

Power will be supplied at from 500 to 550 volts through underground feeders to hard-drawn trolley wires.....S.W.G.

The feeders will be lead-covered, laid in troughing filled in solid with composition and covered with hard burned tiles or other suitable protection, or will be drawn into earthenware ducts.

Detachable swivel trolley heads will be used, and the trolley wire will be in general at a height of about 21 feet, and at a distance horizontally of from 4 to 5 feet from the centre of the track.

The trolley wires will be flexibly suspended from brackets fixed to tubular poles, or in some cases from span wires fastened to poles or to the walls of houses by suitable means, and in such a way as to provide for double insulation throughout between the trolley wires and earth. The bracket arms will have an average length of . . . feet, and will in no case exceed . . . feet in length.

Section switches will be provided at every half mile, either in pillar boxes or in boxes attached to the poles or to houses. Feeder switches will be provided in pillar boxes, and all pillar boxes will be arranged to prevent explosion of gas accumulating in them or in ducts connected with them.

The accompanying plan on a scale of six inches to one mile gives a diagram of the feeders, feeding points, return feeders, earthplates, and pilot wire points.

TRAMWAYS AND LIGHT RAILWAYS LAID ON PUBLIC ROADS
MEMORANDUM REGARDING DETAILS OF CONSTRUCTION OF
NEW LINES AND EQUIPMENT

(NOTE.—*These requirements and recommendations apply only to matters undertaken after the date of the Memorandum*)

(1) *Clearance*

(a) The space between the inner rails of a double line must depend upon the overhang of the cars. It is, however, necessary that there should be at least 15 inches between the sides of passing cars and also a similar space between the side of a car and any standing work such as lamp, telegraph and trolley wire posts in a street.

(b) Side posts should be placed inside the kerb at a sufficient distance from it to prevent the possibility of road vehicles coming into contact with them, due regard being had to the camber of the road.

(c) There should be at least 15 inches between the side of a car and the kerb, whether on straight or curved roads.

(d) The clearance between the top deck of uncovered cars and the underside of bridges should not, if possible, be less than 6 feet 6 inches. Where this clearance cannot be obtained, special precautions in working will be required, but in no case will less than 6 feet be accepted.

(2) *Posts and Brackets*

(a) Centre posts should not be used without the consent, in every case, of the Board of Trade.

(b) The stone kerbing round centre posts should not be such as to enable any person to stand upon it as a refuge, unless the clearance is ample for safety.

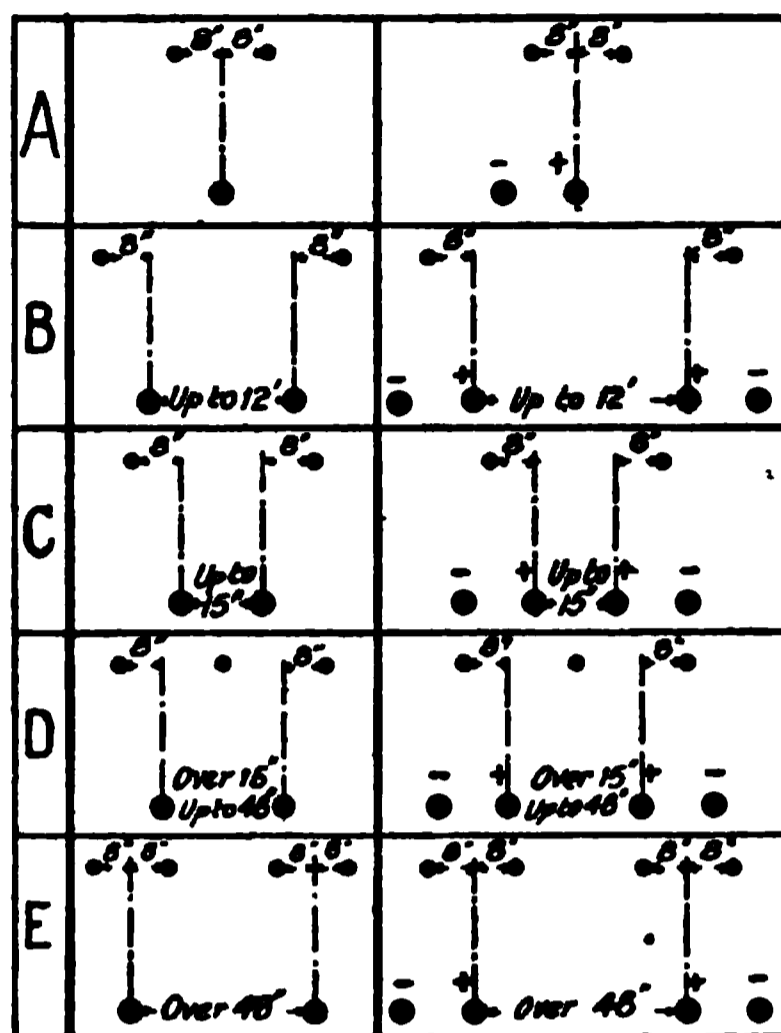
(c) Where bracket arms 16 feet in length will not suffice, it is desirable that span wire construction should be used.

(d) The overhead conductors used in connection with the working of the lines should be securely attached to supports, the intervals between which should not, except with the approval of the Board of Trade, exceed 120 feet, and the overhead conductors should (as a general rule) be in no part at a less height from the surface of the street than 20 feet, except where they pass under bridges.

(e) The overhead conductors should be divided up into sections not exceeding (except with the special approval of the Board of Trade) one-half of a mile in length, between every two of which should be inserted an emergency switch so enclosed as to be inaccessible to pedestrians.

(f) No gas lamp brackets shall be attached to any pole unless triple insulation is provided between the overhead conductors and the pole.

(7) Where the distance between the two positive trolley wires exceeds 48 inches, each trolley wire should be separately guarded (see Fig. E).



Overhead Trolley Tramways. Trackless (Railless) Trolley Routes.

(8) It is desirable, where possible, to divert telegraph wires from above trolley junctions and trolley-wire crossings, and undertakers should endeavour to make arrangements to that effect with the owners of telegraph wires.

TELEGRAPH WIRES PARALLEL TO TROLLEY WIRES

Classes (a) and (b)

(9) Where telegraph wires not crossing a trolley wire are liable to fall upon or to be blown on to a trolley wire, a guard wire should be so erected that a falling wire must fall on the guard wire before it can fall on the trolley wire.

If the trolley wire is within the angle formed by the vertical plane of a telegraph wire, and an imaginary plane drawn at an angle of 45° from the uppermost telegraph wire on the side nearest to the trolley wire, a guard wire should be erected on span wires or on the brackets. This indicates the minimum requirements. In very exposed situations or for heavy routes of wires, more than one guard wire may be needed.

(10) When guard wires are attached to other supports than the trolley poles they should be connected with the rails at one point at least.

(11) When it is possible that a telegraph wire may fall on an arm or a stay, or a span wire, and so slide down on to a trolley wire, guard hooks should be provided.

GENERAL

(12) Minimum guarding requirements for Classes (a) and (b) are provided for in this memorandum, but in exceptional cases, such as in very exposed positions, or for unusually heavy telegraph wires, special precautions should be taken.

APPENDIX II

STANDARDISATION RULES OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

STANDARDS FOR ELECTRIC RAILWAYS

RATING OF RAILWAY SUBSTATION MACHINERY

- 763 **Continuous Rating.**—The rating of a substation machine shall be the kv-a. output at a stated power-factor input, which it will deliver continuously with temperatures or temperature rises not exceeding the limiting values given in §§ 376 and 379.*
- 764 **Momentary Loads.**—These machines should be capable of carrying a load of twice their rating for one minute, after a continuous run at rated load, without disqualifying them for continuous service.
- 765 **Nominal Rating.**—Where the continuous rating is inconvenient, the following nominal rating may be used. The nominal rating of a substation machine shall be the kv-a. output at a stated power-factor input, which, having produced a constant temperature in the machine, may be increased 50 per cent. for two hours, without producing temperatures or temperature rises exceeding by more than 5° C. the limiting values given in §§ 376 and 379. These machines should be capable of carrying a load of twice their nominal rating for a period of one minute, without disqualifying them for continuous service. The name plate should be marked "nominal rating."

CONDUCTOR AND RAIL SYSTEMS

- 774 **STANDARD GAUGE OF CONDUCTOR RAILS.**†—The gauge of conductor rails shall be not less than 26 in. and not more than 27 in.
- 775 **STANDARD ELEVATION OF CONDUCTOR RAILS.**†—The elevation of conductor rails shall be not less than 2½ in., and not more than 3½ in.
- 779 **Classes of Construction.**—Overhead trolley construction will be classed as *Direct Suspension* and *Messenger or Catenary Suspension*.
- 780 **DIRECT SUSPENSION.**—All forms of overhead trolley construction in which the trolley wires are attached, by insulating devices, directly to the main supporting system.
- 781 **MESSENGER OR CATENARY SUSPENSION.**—All forms of overhead trolley construction in which the trolley wires are attached, by suitable devices, to one or more messenger cables, which in turn may be

* Sections 376 and 379 are given on pp. 650, 651.

† These Rules refer to conductor rails placed on either side of the track rails.

carried either in *Simple Catenary*, i.e. by primary messengers, or in *Compound Catenary*, i.e. by secondary messengers.

782 SUPPORTING SYSTEMS shall be classed as follows :

783 SIMPLE CROSS-SPAN SYSTEMS.—Those systems having at each support a single flexible span across the track or tracks.

784 MESSENGER CROSS-SPAN SYSTEMS.—Those systems having at each support two or more flexible spans across the track or tracks. the upper span carrying part or all of the vertical load of the lower span.

785 BRACKET SYSTEMS.—Those systems having at each support an arm or similar rigid member, supported at only one side of the track or tracks.

786 BRIDGE SYSTEMS.—Those systems having at each support a rigid member, supported at both sides of the track or tracks.

787 STANDARD HEIGHT OF TROLLEY WIRE ON STREET AND INTERURBAN RAILWAYS.—It is recommended that supporting structures shall be of such height that the lowest point of the trolley wire shall be at a height of 18 feet above the top of rail under conditions of maximum sag, unless local conditions prevent. On trackage operating electric and steam road equipment and at crossings over steam roads, it is recommended that the trolley wire shall be not less than 21 feet above the top of rail, under conditions of maximum sag.

RAILWAY MOTORS

RATING

800 **Nominal Rating.**—The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90° C. at the commutator, and 75° C. at any other normally accessible part after one hour's continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature as measured by resistance shall not exceed 100° C.*

801 The statement of the nominal rating shall also include the corresponding voltage and armature speed.

802 **Continuous Rating.**—The continuous ratings of a railway motor shall be the *inputs* in amperes at which it may be operated continuously at $\frac{1}{2}$, $\frac{3}{4}$, and full voltage respectively, without exceeding the specified temperature rises (see § 805), when operated on stand test with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to define the system of ventilation which is used. In case motors are cooled by external blowers, the flow of air on which the rating is based shall be given.

803 **Maximum Input.**—The subject of momentary loads for railway motors is under investigation.

TEMPERATURE LIMITATIONS

804 The allowable temperature in any part of a motor in service will be governed by the kind of material with which that part is insulated. In view of space limitations, and the cost of carrying dead weight on

* This definition differs from that in the 1911 edition of the Rules, principally by the substitution of a kilowatt rating for the horse-power rating and the omission of a reference to a room temperature of 25° C.

cars, it is considered good practice to operate railway motors for short periods at higher temperatures than would be advisable in stationary motors. The following temperatures are permissible :

OPERATING TEMPERATURES OF RAILWAY MOTORS

Class of Material.*	Maximum Observable Temperature of Windings when in Continuous Service.	
	By Thermometer.	By Resistance.
A	85	110
B	100	130

* See §§ 376, 379 (pp. 650, 651).

For infrequent occasions, due to extreme ambient temperatures, it is permissible to operate at 15° higher temperature.

805 With a view to not exceeding the above temperature limitations, the continuous ratings shall be based upon the temperature rises tabulated below :

STAND-TEST TEMPERATURE RISES OF RAILWAY MOTORS †

Class of Material.*	Temperature Rises of Windings.	
	By Thermometer.	By Resistance.
A	65	85
B	80	105

* See §§ 376, 379 (pp. 650, 651).

806 **Field-control Motors.**—The nominal and continuous ratings of field-control motors shall relate to their performance with the operating field which gives the maximum motor rating. Each section of the field windings shall be adequate to perform the service required of it, without exceeding the specified temperature rises.

CHARACTERISTIC CURVES

810 The characteristic curves of railway motors shall be plotted with the current as abscissæ, and the tractive effort, speed, and efficiency as ordinates. In the case of alternating-current motors, the power-factor shall also be plotted as ordinates.

811 Characteristic curves of continuous-current motors shall be based upon full voltage, which shall be taken as 600 volts, or a multiple thereof.

812 In the case of field-control motors, characteristic curves shall be given for all operating field connections.

† The temperature rise in service may be very different from that on stand test. See § 1104 for relation between stand test and service temperatures, as affected by ventilation.

EFFICIENCY AND LOSSES

- 815 The efficiency of railway motors shall be deduced from a determination of the losses enumerated in §§ 816 to 820. (See also §§ 1100 and 1101.)
- 816 The copper loss shall be determined from resistance measurements corrected to 75° C.
- 817 The no-load core loss, brush friction, armature-bearing friction and windage shall be determined as a total under the following conditions :

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. With the field separately excited, such a voltage shall be applied to the armature terminals as will give the same speed for any given field current as is obtained with that field current when operating at normal voltage under load. The sum of the losses above-mentioned is equal to the product of the counter electromotive force and the armature current.

- 818 The core loss in continuous-current motors shall be separated from the friction and windage losses above described by measuring the power required to drive the motor at any given speed without gears, by running it as a series motor on low voltage and deducting this loss from the sum of the no-load losses at corresponding speed. (See § 1101 for alternative method.)

The friction and windage losses under load shall be assumed to be the same as without load, at the same speed.

The core loss under load shall be assumed as follows :

CORE LOSS IN CONTINUOUS-CURRENT RAILWAY MOTORS
AT VARIOUS LOADS

Per cent. of Input at Nominal Rating.	Loss as per cent. of No-load Core Loss.
200	165
150	145
100	130
75	125
50	123
25 and under.	122

NOTE.—With motors designed for field control the core losses shall be assumed as the same for both full and permanent field. It shall be the mean between the no-load losses at full and permanent field, increased by the percentages given in the above Table.

- 819 The brush-contact resistance loss to be used in determining the efficiency may be obtained by assuming that the sum of the drops at the contact surfaces of the positive and negative brushes is three volts
- 820 The losses in gearing and axle bearings for single-reduction single-g geared motors varies with type, mechanical finish, age, and lubrication. The following values, based on accumulated tests, shall be used in the comparison of single-reduction single-g geared motors :

LOSSES IN AXLE BEARINGS AND SINGLE-REDUCTION GEARING
OF RAILWAY MOTORS

Per cent. of Input at Nominal Rating.	Losses as per cent. of Input.
200	3.5
150	3.0
125	2.7
100	2.5
75	2.5
60	2.7
50	3.2
40	4.4
30	6.7
25	8.5

NOTE.—Further investigation may indicate the desirability of giving separate values of the losses for full and tapped fields, or low- and high-speed motors.

ELECTRIC LOCOMOTIVES

830 **Rating.**—Locomotives shall be rated in terms of the weight on drivers, nominal one-hour tractive effort, continuous tractive effort, and corresponding speeds.

831 **Weight on Drivers.**—The weight on drivers, expressed in pounds, shall be the sum of the weights carried by the drivers and of the drivers themselves.

832 **Nominal Tractive Effort.**—The nominal tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers, when the motors are operating at their nominal (one-hour) rating.

833 **Continuous Tractive Effort.**—The continuous tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their full-voltage continuous rating, as indicated in § 802.

In the case of locomotives operating on intermittent service, the continuous tractive effort may be given for $\frac{1}{2}$ or $\frac{3}{4}$ voltage, but in such cases the voltage shall be clearly specified.

834 **Speed.**—The rated speed, expressed in miles per hour, shall be that at which the continuous tractive effort is exerted.

ADDITIONAL STANDARDS FOR RAILWAY MOTORS

1100 In comparing projected motors, and in case it is not possible or desirable to make tests to determine mechanical losses, the following values of these losses, determined from the averages of many tests over a wide range of sizes of single-reduction single-gearred motors, will be found useful as approximations. They include axle-bearing, gear, armature-bearing, brush-friction, windage, and stray-load losses.

APPROXIMATE LOSSES IN CONTINUOUS-CURRENT RAILWAY MOTORS

Per cent. of Input at Nominal Rating.	Losses as per cent. of Input.
100 or over.	5.0
75	5.0
60	5.3
50	6.5
40	8.8
30	13.3
25	17.0

1101 The core loss of railway motors is sometimes determined by separately exciting the field, and driving the armature of the motor to be tested by a separate motor having known losses, and noting the differences in losses between driving the motor light at various speeds and driving it with various field excitations.

1102 **Selection of Motor for Specified Service.**

The following information relative to the service to be performed is required in order that an appropriate motor may be selected:

- (a) Weight of total number of cars in train, exclusive of electrical equipment and load.
- (b) Average weight of load and duration of same, and maximum weight of load and duration of same.
- (c) Number of motor-cars or locomotives in train, and number of trailer cars in train.
- (d) Diameter of driving wheels.
- (e) Weight on driving wheels, exclusive of electrical equipment.
- (f) Number of motors per motor-car.
- (g) Voltage at train with power on the motors—average, maximum, and minimum.
- (h) Acceleration in ml.p.h.p.s.
- (i) Rate of braking (retardation in ml.p.h.p.s.).
- (j) Speed limitations, if any (including slowdowns).
- (k) Distances between stations.
- (l) Duration of station stops.
- (m) Schedule speed, including station stops, in ml.p.h.
- (n) Train resistance in pounds per ton at stated speeds.
- (o) Moment of inertia of revolving parts, exclusive of electrical equipment.
- (p) Profile and alignment of track.
- (q) Distance coasted as a per cent. of the distance between station stops.
- (r) Time of layover at end of run, if any.

1103 **Stand-test Method of Comparing Motor Capacity with Service Requirements.**—When it is not convenient to test motors under actual specific service conditions, recourse may be had to the following method of determining temperature rise:

1104 The essential motor losses affecting temperatures in service are those in the motor windings, core, and commutator. The mean service conditions may be expressed, as a close approximation, in terms of that continuous current and core loss which will produce the same losses and distribution of losses as the average in service.

A stand test with the current and voltage which will give losses equal to those in service will determine whether the motor has sufficient capacity to meet the service requirements. In service, the temperature rise of an enclosed motor, well exposed to the draught of air incident to a moving car or locomotive, will be from 75 to 90 per cent. (depending upon the character of the service) of the temperature rise obtained on a stand test with the motor completely enclosed and with the same losses. With a ventilated motor the temperature rise in service will be 90 to 100 per cent. of the temperature rise obtained on a stand test with the same losses.

1105 In making a stand test to determine the temperature rise in a specific service, it is essential in the case of a self-ventilated motor to run the armature at a speed which corresponds to the schedule speed in service. In order to obtain this speed it may be necessary, while maintaining the same total armature losses, to change somewhat the ratio between the I^2R and core-loss components.

1106 **Calculation for Comparing Motor Capacity with Service Requirements.**—The heating of a motor should be determined, wherever pos-

sible, by testing it in service, or with an equivalent duty cycle. When the service or equivalent duty-cycle tests are not practicable, the ratings of the motor may be utilised as follows to determine its temperature rise.

1107 The motor losses which affect the heating of the windings are, as stated above, those in the windings and in the core. The former are proportional to the square of the current. The latter vary with the voltage and current, according to curves which can be supplied by the manufacturers. The procedure is therefore as follows:

1108 (a) Plot a time-current curve, a time-voltage curve, and a time-core loss curve for the duty cycle which the motor is to perform, and calculate from these the root-mean-square current and the average core loss.

1109 (b) If the calculated r.m.s. service current exceeds the continuous rating, when run with average service core loss and speed, the motor is not sufficiently powerful for the duty cycle contemplated.

1110 (c) If the calculated r.m.s. service current does not exceed the continuous rating, when run with average service core loss and speed, the motor is ordinarily suitable for the service. In some cases, however, it may not have sufficient thermal capacity to avoid excessive temperature rises during the periods of heavy load. In such cases a further calculation is required, the first step of which is to compute the equivalent voltage which, with the r.m.s. current, will produce the average core loss. Having obtained this, determine, as follows, the temperature rise due to the r.m.s. service current, and equivalent voltage.

$$\begin{array}{l} \text{Let } \theta = \text{temperature rise} \\ p_0 = I^2 R \text{ loss, kw.} \\ p_c = \text{core loss, kw.} \end{array} \left\{ \begin{array}{l} \text{with r.m.s. service current, and equivalent} \\ \text{service voltage.} \end{array} \right.$$

$$\begin{array}{l} \Theta = \text{temperature rise} \\ P_0 = I^2 R \text{ loss, kw.} \\ P_c = \text{core loss, kw.} \end{array} \left\{ \begin{array}{l} \text{with continuous load current corresponding} \\ \text{to the equivalent service voltage.} \end{array} \right.$$

Then

$$\theta = \Theta \frac{p_0 + p_c}{P_0 + P_c}, \text{ approximately.}$$

1111 (d) The thermal capacity of a motor is approximately measured by the ratio of the electrical loss in kw. at its nominal (one-hour) capacity, to the corresponding maximum observable temperature rise during a one-hour test starting at ambient temperature.

1112 (e) Consider any period of peak load and determine the electrical losses in kilowatt-hours during that period from the *electrical* efficiency curve. Find the excess of the above losses over the losses with r.m.s. service current and equivalent voltage. The excess loss, divided by the coefficient of thermal capacity, will equal the extra temperature rise due to the peak load. This temperature rise added to that due to the r.m.s. service current, and equivalent voltage, gives the total temperature rise. If the total temperature rise in any such period exceeds the safe limit, the motor is not sufficiently powerful for the service.

1113 (f) If the temperature reached, due to the peak loads, does not exceed the safe limit, the motor may yet be unsuitable for the service, as the peak loads may cause excessive sparking and dangerous mechanical stresses. It is, therefore, necessary to compare the peak loads with the short-period overload capacity. If the peaks are also within the capacity of the motor, it may be considered suitable for the given duty cycle.

TEMPERATURE LIMITS

375 Table A gives the limits for the hottest-spot temperatures of insulations. The permissible limits are indicated in column 1 of the Table.

The limits of temperature rise permitted under rated-load conditions are given in column 2, and are found by subtracting 40° C. from the figures in column 1. Whatever be the ambient temperature at the time of the test, the rise of temperature must never exceed the limits in column 2 of the Table. The highest temperatures, and temperature rises, attained in any machine at the output for which it is rated, must not exceed the values indicated in the Table and clauses following.

376 **Permissible Temperatures and Temperature Rises for Insulating Materials.**—Table A gives the highest temperatures and temperature rises to which various classes of insulating materials may be subjected, based on a standard ambient temperature of reference of 40° C.

TABLE A
PERMISSIBLE TEMPERATURES AND TEMPERATURE RISES FOR
INSULATING MATERIALS

Class.	Description of Material.	1 Maximum Temperature to which the Material may be subjected.	2 Maximum Temperature Rise.
A	Cotton, silk, paper, and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enamelled wire	105° C.*	65° C.*
B	Mica, asbestos, and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only, and may be destroyed without impairing the insulating or mechanical qualities of the insulation	125° C.	85° C.
C	Fireproof and refractory materials, such as pure mica, porcelain, quartz, &c. .	No limits specified.	

377 **NOTE.**—The Institute recognises the ability of manufacturers to employ Class B insulation successfully at maximum temperatures of 150° C. and even higher. However, as sufficient data covering experience over a period of years at such temperatures is at present unavailable, the Institute adopts 125° C. as a conservative limit for this class of insulation, and any increase above this figure should be the subject of special guarantee by the manufacturer.

[**AUTHOR'S NOTE.**—Table B gives the limiting observable temperatures corresponding to given permissible hottest-spot temperatures. Obviously, when the hottest-spot temperature is fixed, the permissible observable temperature will depend on the method of measuring the temperature. The methods available in practice are: (I) by thermometer; (II) by resistance measurement; (III) by means of embedded temperature detectors built into the machine. Of these methods, the first is the least satisfactory for obtaining the true temperature of the hottest part of the insulation, so that, in this case, a “hottest-spot correction” of 15° C. (see Table) is applied to the observed temperatures in order to obtain an approximation to the true temperature of the hottest part.]

* For cotton, silk, paper, and similar materials, when neither impregnated nor immersed in oil, the highest temperatures and temperature rise shall be 10° C. below these values.

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TABLE B

PERMISSIBLE HOTTEST-SPOT TEMPERATURES AND LIMITING OBSERVABLE TEMPERATURE RISES IN OTHER THAN WATER-COOLED MACHINERY

	Class A.*	Class B.
Permissible Hottest-spot Temperature . . .	105°	125°
METHOD I. Thermometer only :—		
Hottest-spot Correction	15°	15°
Limiting Observable Temperature	90°	110°
Limiting Observable Temperature Rise above 40° C.	50°	70°
METHOD II. Resistance :—		
Hottest-spot Correction	10°	10°
Limiting Observable Temperature	95°	115°
Limiting Observable Temperature Rise above 40° C.	55°	75°
METHOD III. Embedded Temperature Detectors :—		
Double-Layer Windings. For all Voltages. {		
Hottest-spot Correction	5°	5°
Limiting Observable Temperature	100°	120°
Limiting Observable Temperature Rise above 40° C.	60°	80°
Single-Layer Windings. For 5000 volts or less. {		
Hottest-spot Correction	10°	10°
Limiting Observable Temperature	95°	115°
Limiting Observable Temperature Rise above 40° C.	55°	75°
Single-Layer Windings. For more than 5000 volts. {		
Hottest-spot Correction	$10^{\circ} + (E - 5)^{\dagger}$	$10^{\circ} + (E - 5)$
Limiting Observable Temperature	$95^{\circ} - (E - 5)$	$115^{\circ} - (E - 5)$
Limiting Observable Temperature Rise above 40° C.	$55^{\circ} - (E - 5)$	$75^{\circ} - (E - 5)$

* For cotton, silk, paper, and similar materials, when neither impregnated nor immersed in oil, the highest temperatures and temperature rise shall be 10° C. below the limits fixed for class A.

† In these formulæ, *E* represents the rated pressure between terminals in kilovolts. Thus for a three-phase machine with single-layer winding, and with 11 kilovolts between terminals, the hottest-spot correction to be added to the maximum observable temperature will be 16° C.

APPENDIX III

FOLLOWING are references to selected articles and papers in which are given detailed information relating to electric railways and tramways.

Abbreviations: *T.R.W.*, *Tramway and Railway World*; *E.*, *Electrician*; *E.R.*, *Electrical Review*; *Er.*, *The Engineer*; *Eg.*, *Engineering*; *E.R.J.*, *Electric Railway Journal*; *I.E.E.*, *Journal of the Institution of Electrical Engineers*; *A.I.E.E.*, *Transactions of the American Institute of Electrical Engineers*; *I.C.E.*, *Minutes of Proceedings of the Institution of Civil Engineers*.

BRITISH RAILWAYS

North-Eastern: *T.R.W.* 15, 17 *†, 267 ‡ (550-volt lines); 39, 413 *† (1500-volt lines).

Lancashire and Yorkshire: *T.R.W.* 15, 35, 353 *†‡; 20, 9 (600-volt lines); 35, 276 (3750-volt lines); 39, 17 *†‡ (1200-volt lines).

Metropolitan District: *T.R.W.* 17, 97 *†‡; 18, 119; 23, 342; 26, 87; 29, 77.

Metropolitan: *T.R.W.* 16, 17 *†‡; 33, 269.

London Electric (Tubes)—City and South London: *E.* 48, 166 *†, etc.; *I.E.E.* 33, 100 *†; *T.R.W.* 21, 372. Waterloo and City: *I.C.E.* 139, 25, 56.*† Central London: *E.R.* 46, 926 *†‡, etc.; *Er.* 114, 564; *T.R.W.* 9, 531 *†‡; 21, 372; 32, 97. Great Northern and City: *E.R.* 54, 134, 179 †, 344.* Baker Street and Waterloo: *T.R.W.* 17, 491; 19, 197.*† Great Northern, Piccadilly and Brompton: *T.R.W.* 20, 519.*† Charing Cross, Euston and Hampstead: *T.R.W.* 22, 1 *; 34, 483.

Great Western (Hammersmith and City): *T.R.W.* 20, 21; 22, 89.*†‡

London and South-Western: *T.R.W.* 38, 361.*†‡

London and North-Western: *T.R.W.* 35, 349; 37, 13.

Mersey: *T.R.W.* 13, 323 *†; *I.C.E.* 179, 19.

London, Brighton and South Coast: *I.C.E.* 186, 29 *; *Eg.* 93, 105, 173, 237, 307, 378, 548; *Er.* 114, 140.

Midland (Morecambe branch): *T.R.W.* 23, 437.*†

AMERICAN RAILWAYS

New York Central: *T.R.W.* 25, 9 *†‡; 33, 415.

New York Subway and Interborough Rapid Transit: *T.R.W.* 16, 447.*†‡

Pennsylvania: *Er.* 121, 221 *†.

New York, New Haven and Hartford: *A.I.E.E.* 27, 43, 1613; 30, 1391.

Butte, Anaconda and Pacific: *T.R.W.* 35, 267 *†; *A.I.E.E.* 33, 1369.

Chicago, Milwaukee and St. Paul: *T.R.W.* 40, 169.*†‡

Great Northern (Cascade Tunnel): *T.R.W.* 25, 246 *; *A.I.E.E.* 28, 1281.*†

Norfolk and Western: *T.R.W.* 38, 9 *†‡; *E.R.J.* 45, 1058.*†‡

* Article contains detailed description of electrification, including track, rolling stock, distributing system.

† Article contains description of generating station. In many cases detailed drawings are included.

‡ Article contains description of sub-stations. In many cases detailed drawings and diagrams of switchboard connections are included.

CONTINENTAL RAILWAYS

Italian State: *Er.* 116, 216, 242, 269, 297†, 643; 117, 89, 115, 143, 174; *T.R.W.* 27, 345; 33, 334; 35, 183*; 36, 391‡; 40, 93.

Simplon Tunnel: *E.* 57, 921*; 72, 58.

Lötschberg-Simplon: *Er.* 113, 116, 144; 114, 672; 116, 17, 540, 596.

Midi: *I.E.E.* 51, 555*; *Er.* 115, 118, 153, 172, 437.

Rotterdam-Hague: *Er.* 114, 70.*

Prussian State: *Er.* 113, 438, 455, 480, 522; 115, 194; *E.* 68, 461.

BRITISH TRAMWAYS

London: *T.R.W.* 13, 437*††; 19, 14, 415; 21, 25, 463*†; 24, 1*††, 93; 25, 91; 26, 167*; 288, 375; 29, 229; *I.E.E.* 43, 235.*††

Glasgow: *T.W.R.* 30, 171.*††

Manchester: *T.R.W.* 15, 237, 375*††; 22, 189.

Birmingham: *T.R.W.* 21, 9.*

Liverpool: *T.R.W.* 16, 215.*†

Dublin: *T.R.W.* 27, 333.*

Belfast: *T.R.W.* 18, 333.*†

Leeds: *T.R.W.* 20, 205*†; 29, 157.

Bradford: *T.R.W.* 28, 184*†; 29, 237; 30, 9.

Sheffield: *T.R.W.* 34, 197.*†

Bournemouth: *T.R.W.* 13, 17; 18, 456; 21, 99.

Bristol: *T.R.W.* 8, 85.*†

Hastings and District: *T.R.W.* 18, 357.*††

* Article contains detailed description of electrification, including track, rolling stock, distributing system.

† Article contains description of generating station. In many cases detailed drawings are included.

‡ Article contains description of sub-stations. In many cases detailed drawings and diagrams of switchboard connections are included.

EXAMPLES

THIS collection of examples includes questions set at the following examinations:—

University of London, B.Sc. Eng.* Reference *L. U.*

City and Guilds of London Institute, Electrical Engineering. Reference *C. & G.*

Institution of Electrical Engineers, A.M.I.E.E. Examination. Reference *I. E. E.*

Battersea Polytechnic, Final Diploma Electrical Engineering. Reference *B. P.*

The examples have been grouped according to the subject matter and chapters.

TRAIN MOVEMENT.—CHAPTERS II AND III

1. A tramcar usually traverses half a mile between two stopping-places in $2\frac{1}{2}$ minutes. It is stopped twice, for 5 seconds and 10 seconds respectively, to take up passengers. What is the average speed for the normal and for the stopping run? (*I. E. E.* 1914.) [Ans. 12 ml.p.h. ; 10.9 ml.p.h.]

2. An electric train runs with an average speed of 22 miles per hour. The average distance between station stops is 1 mile, and the train stops 20 seconds at each station. What is the effect on the schedule speed of doubling the average speed and making the stops 30 seconds? What is the resulting average schedule speed? (*I. E. E.* 1914.)

[Ans. Schedule speed increased 63.6 per cent. Resulting average schedule speed = 32.1 ml.p.h.]

3. Draw a typical speed-time curve for an electric train operating on suburban service, and state the values usually adopted for the acceleration and rate of braking. Show how the actual speed-time curve is modified for preliminary calculations, and explain the object of these modifications.

A suburban service, with an average of $1\frac{1}{2}$ miles between stations, is to be operated at a schedule speed of 25 ml.p.h., with stops of 20 seconds duration. If the maximum speed is 20 per cent. higher than the average speed, find the acceleration required. The rate of braking is 2 ml.p.h.p.s. (*B. P.* 1915).

[Ans. Acceleration = 1.08 ml.p.h.p.s.]

4. Show how the simplified speed-time curve for an electric train is developed from the actual speed-time curve. Of what use is the former in electric railway engineering?

Obtain an expression for the acceleration required for a given train service, the rate of braking and the ratio (maximum speed/average speed) being known.

* The Engineering Examination Papers of the University of London are published regularly by the University of London Press, and may be obtained through Messrs. Hodder & Stoughton.

An urban railway, with stations 2560 feet apart, operates at a schedule speed of 16 ml.p.h. The duration of stop is 20 seconds and the braking retardation is 2 ml.p.h.p.s. Calculate the acceleration required, assuming that the maximum speed is 22 per cent. higher than the average speed. (B.P. 1916.)

[Ans. Acceleration = 1.2 ml.p.h.p.s.]

5. The draw-bar pull of an electric locomotive hauling a goods train of 320 tons on the level is 1 ton at 20 miles per hour. What does the pull become on a gradient of 1 in 80 in order to keep the speed the same up the grade as on the level. (I.E.E. 1914.)

[Ans. 4.95 tons.]

6. A tramcar weighing 8 tons is required to travel up a bank of 1 in 20 at a speed of 8 miles per hour, the running friction being 20 lb. per ton. Find approximately the current taken at 500 volts when the two motors are in series. (L. U. 1910.)

[Ans. 45 amp.]

7. How is the energy consumption of an electric train, making a given schedule speed, affected by (a) the distance between the stations, (b) the acceleration, and (c) the rate of braking? What are the objections to operating a train service, with short distances between stations, at a high schedule speed? State exactly the manner in which the rate of braking affects the energy consumption for a given schedule speed and acceleration. (B.P. 1913.)

8. Show how the acceleration of the revolving parts of a train is allowed for in calculations relating to train movement. Calculate the effective weight of the six-coach train of which data follows:

Composition of train: 2 motor-coaches, 4 trailer-coaches.

Motor-coaches: Weight, 27.5 tons. Equipment: one 4-wheel motor-truck with 36-in. wheels and two 200-H.P. motors, gear ratio 3.2:1; one 4 wheel trailer-truck with 30-in. wheels. Diameter of armatures, 18.5 in. Weight of armatures, 1800 lb. each.

Trailer-coaches: Weight, 16.2 tons. Equipment: two 4-wheel trucks with 30-in. wheels.

Weight of wheels: Motor-trucks, 900 lb. each; trailer-trucks 650 lb. each.

NOTE.— k/r may be taken as 0.77 for wheels and 0.7 for armatures.

k =radius of gyration, r =external radius. (B.P. 1912.)

[Ans. 133 tons.]

9. Make a *preliminary* estimation of the energy consumption for a six-coach electric train running between two stations $1\frac{1}{2}$ miles apart at an average speed of 26 miles per hour. There is a uniform "up" gradient of 1 in 175 between the stations. The acceleration and braking retardation on level track are respectively 1.0 and 2.0 ml.p.h.p.s. Weight of train=215 tons. Effective weight=243 tons. Train resistance may be taken at 10 lb. per ton at all speeds. (B.P. 1911.)

[Ans. 64.8 wh./t.ml.]

MOTORS.—CHAPTERS IV–VII

10. For the frequent stopping and starting essential to urban and suburban tramway or railway service what type of continuous-current motor is in general use and why? (I.E.E. 1914.)

11. Why are motors possessing a "series" characteristic used for electric traction? Under what conditions could motors possessing a "shunt" characteristic be adopted?

How is the division of load between two series motors on a tramcar affected by: (a) wear of the wheels, (b) a difference in the speed curves of the motors? (B.P. 1915.)

12. The air gap of one of the series motors on a tramcar is slightly less than that of the other, but the motors are otherwise alike. How will they

share the load between them when (a) in full series, and (b) in full parallel. Give reasons for your answers, and say how the differences may be approximately compensated. (*L. U.* 1910.)

13. The 500-volt motors on a tramcar have resistances of 0.3 ohm and 0.2 ohm for field and armature respectively. When running in full parallel, at an efficiency of 88 per cent. and at 660 r.p.m., each develops a torque of 180 lb.-ft. Determine the percentage weakening of the field required to increase the speed to 720 r.p.m., the torque remaining unchanged. (*L. U.* 1911.)
[*Ans.* 8.6 per cent.]

14. In what way has the introduction of commutating poles into traction motors led to a reduction in the energy required per car mile? Describe the necessary modifications in the controller. (*L. U.* 1912.)

15. Draw a vector diagram for a single-phase commutator motor and explain how the terminal voltage is built up from the internal voltages; show how the power-factor is determined from the diagram. (*L. U.* 1912.)

16. Describe some form of single-phase commutator motor, and explain with the help of vector diagrams its mode of operation under different conditions of load. Why is commutation more difficult than in a continuous-current motor? How are these difficulties overcome? (*L. U.* 1915.)

17. How does the problem of commutation in the continuous-current series motor differ from that in the same type of motor intended for alternate currents? Compare the methods used in practice for obtaining satisfactory commutation in the alternate-current commutator motor. (*L. U.* 1915.)

18. Discuss the question of the most suitable frequency for single-phase main line traction. (*C. & G.* 1911.)

19. State the advantages of cascade control of induction motors for traction work. Define the term "cascade synchronous speed." (*L. U.* 1911.)

20. Show how to calculate the performance curves of a continuous-current traction motor. Assume all the necessary data for one value of the current, and the curves connecting the current with the field strength and with the iron losses. Show how to find, for different currents, the speed, the brake H.P., the efficiency, and the torque. (*L. U.* 1913.)

CONTROL.—CHAPTERS VIII–XII

21. What are the advantages of the series-parallel system of control as applied to electric traction by means of continuous currents? Give diagrams showing the connections made at each step during starting and braking. Show by a diagram what is the saving in energy secured by this method during starting. What further saving can be secured by using four motors instead of two? (*L. U.* 1915.)

22. Explain the series-parallel system of control as applied to electric traction. Neglecting the resistances of the motors, show that, with constant motor current and constant line voltage, the rheostat losses during starting two motors on the series-parallel system are one-half of those when the motors are started on the rheostatic system (*i.e.*, both motors in parallel throughout the starting period).

Explain the various methods of transition from series to parallel, and mention the suitability of these methods for (a) tramway service, (b) suburban railway service with motor-coach trains. (*B. P.* 1916.)

23. A tramcar, or the motor-coach of an electric train, is equipped with two continuous-current series motors. Give a diagram showing first series and then parallel connections of the motors, with the successive cutting out of the resistances from the motor circuit, assuming four controller notches with the motors in series and four with the motors in parallel. (*I. E. E.* 1914.)

24. Show, by means of diagrams, how the transition from "series" to "parallel" is effected in a modern tramcar controller. Explain the "bridge" method of transition, and state the advantages of this method for heavy suburban services. (*B. P.* 1915.)

25. Show two methods of connecting the motors on a tramcar for electric braking, stating what alterations are necessary in the connections between running and braking. (Part question: *B.P.* 1914.)

26. What conditions have to be satisfied when traction motors have to be used for electric braking? Show, by means of diagrams, alternative methods for connecting up the motors, rheostats, and magnetic track-brakes. (Part question: *L. U.* 1915.)

27. Draw a diagram showing the connections of a controller suitable for effecting a series-parallel control of two series motors. Steps are to be provided for electric braking, but no provision need be made for reversing. (*L. U.* 1915.)

28. Explain the principle of the multiple-unit system of train control. What are the advantages of this system for motor-coach trains? What apparatus is required on (a) each motor-coach, (b) each trailer-coach of the train?

How can the system be adapted for automatic control? (*B.P.* 1916.)

29. Explain the action of a "limit switch" in connection with continuous-current traction controller systems. Give a diagram of the main connections in a particular system of control, and show how the limit switch is introduced. (*L. U.* 1909.) [*Author's Note.*—The term "limit switch" is here used to denote the simplified form of accelerating relay without potential coils. See Figs. 159, 160, 163, 166, pp. 187, 189, 193, 196.]

30. Give an approximate method for calculating the values of the resistances for the various steps of a tramway controller on the series parallel system. (*L. U.* 1912.)

31. Determine the magnitudes of the resistances for the series notches of a tramcar controller to control two 40-H.P., 500-volt, 500 r.p.m. motors. The (hot) resistance of each motor is 0.65 ohm; the current limits during acceleration are 84 and 60 amperes; and the speeds of the car corresponding to these currents are 8.8 and 10.2 ml.p.h., respectively, with normal voltage on each motor.

[*Ans.* $R_1 - R_4 = 4.65$ ohms; $R_2 - R_4 = 2.75$ ohms; $R_3 - R_4 = 1.23$ ohms.]

32. Give diagrams of the connections and describe the methods used for obtaining a variable voltage from a static transformer for the control of a single-phase motor for electric traction. (*L. U.* 1909.)

33. Describe two forms of controlling apparatus used for regulating the voltage applied to a single-phase traction motor when the supply line delivers high-pressure current at a fixed voltage. (*L. U.* 1913.)

34. Make a comparison of the continuous-current and alternating-current contactor systems of control of traction motors. Point out their relative advantages. Sketch a diagram of connections in each case. (*L. U.* 1914.)

35. Sketch and describe a good form of electromagnetic contactor for use in a railway operated on a continuous-current system: point out the difference in design between it and a contactor for use on a single-phase alternating-current system. (*L. U.* 1912.)

36. Describe with sketches one good form of alternating-current electro-magnet, showing how chattering is reduced. What is the importance of such apparatus in single-phase contactor systems? (*L. U.* 1913.)

37. Explain, with sketches, the method of operating a railway train by three-phase induction motors working with "cascade" connections, and describe the gear which is used for starting. What are the chief objections to this system. (*C. & G.* 1913.)

38. Describe the methods of regenerative control met with in continuous-current and in alternating-current traction, and criticise their advantages and disadvantages. Illustrate your answer by suitable diagrams of connections. (*L. U.* 1915.)

39. Discuss the advantages and disadvantages of providing means whereby power can be generated by the motors on a tramcar and returned to the line during the braking period. (*C. & G.* 1913.)

ROLLING STOCK AND LOCOMOTIVES.—CHAPTERS XV–XVII

40. Sketch and describe one good form of magnetic track brake for use on a tramway, and show how it is energised. Calculate the vertical pull and estimate the horizontal drag exerted if the area of each pole is 5 square inches and in which the iron is magnetised to an induction density of 18,000 C.G.S. units. (*L. U.* 1914.)

[*Ans.* Vertical pull = 0.83 ton. Horizontal drag (assuming coefficient of friction = 0.25) = 0.208 ton.]

41. A magnetic track brake for a tramway has to be designed for a pull of one ton. Choose a suitable value for the induction density, and calculate the polar area. How is such a brake energised in practice? (*L. U.* 1915.)

[*Ans.* Polar area (for $B = 18,000$) = 12 sq. in.]

42. Sketch and describe the mechanism by which energy is transmitted to the driving wheels, from two motors, in the case of an electric locomotive. Point out how the mechanism overcomes the difficulties met with in the earlier forms of locomotives. Show how the motors are suspended. (*L. U.* 1914.)

43. Discuss the relative merits of high-pressure single-phase and moderate-pressure continuous-current locomotives for main lines, paying particular attention to the following points: (a) weight of locomotive per H.P., (b) regulation of speed and tractive effort, (c) efficiency, (d) simplicity of design and operation. (*C. & G.* 1914.)

TRAIN RESISTANCE.—CHAPTER XVIII

44. If the resistance to movement of a vehicle requires an input of 2 watt-hours per ton-mile for every pound per ton resistance when the efficiency of conversion is 100 per cent., state what actual input in kilowatt-hours per mile you would expect to supply to the motors:—

(a) For a motor-coach train weighing 100 tons, equipped with 600-volt continuous-current motors, when running continuously at 30 miles per hour on the level.

(b) For a tramcar weighing 35 tons when running continuously at 12 miles per hour on the level. (*I. E. E.* 1914.)

[*Ans.* (a) 2.16. (b) 1.69. NOTE.—Train resistance of motor-coach train = 9.5 lb. per ton. Efficiency of motors = 88 per cent. Resistance of tramcar = 20 lb. per ton. Efficiency of motors = 83 per cent.]

SPEED-TIME CURVES AND ENERGY CONSUMPTION.—CHAPTER XIX

45. Make out a diagram giving approximately the relation between speed, torque and armature current of a 500-volt, continuous-current traction motor, whose normal rating for one hour is 35 H.P. at 600 r.p.m. Choose a suitable gear ratio for use with two such motors on a car and show what average speed can be obtained on the level with a car weighing 15 tons, which makes stops of 10 seconds every two minutes. The running resistance may be taken at 15 lb. per ton and the braking at 150 lb. per ton. Neglect the flywheel effect of the motors. (*C. & G.* 1913.)

[*Ans.* Schedule speed (with 30-in. wheels and 5.36 : 1 gear ratio) = 15 ml.p.h.]

NOTE.—Motors are geared to give a car speed of 10 ml.p.h. at full load. Characteristics of motor (for 30-in. wheels and 5.36 : 1 gear ratio):—

Amperes	65	45	38	30	25	20
Speed (ml.p.h.)	10	12.1	13.2	15.4	17.4	20.2
Tractive effort (lb.)	1310	755	614	410	290	191

46. A six-coach electric train, consisting of two motor-coaches and four trailers, operates on an underground tube railway at a schedule speed of 15 miles per hour with stops of 15 seconds' duration. Calculate the speed-time curve and energy consumption of this train for a run between two stations 0·38 mile apart, assuming the train to be supplied with continuous current at a constant voltage of 550 volts and the track to be level and straight.

The weight of train with passengers is 138·5 tons ; the effective weight is 151·7 tons, and the total length is 300 feet. Each motor-coach is equipped with two 200-H.P., 550-volt continuous-current motors, which are geared to 36-in. wheels, the gear ratio being 3·37:1. The characteristics of the motors at 550 volts are as follows :—

Amperes	350	300	250	200	150	100
Speed (ml.p.h.)	17·5	18·7	20·1	22·9	27·5	37·4
Tractive effort (lb.)	4850	3940	3030	2140	1320	590

The average accelerating current per motor is 300 amperes : the braking retardation is 2 ml.p.h.p.s. : the train resistance may be assumed at 8 lb. per ton for all speeds ; and the apparent train resistance during coasting may be assumed at 11·3 lb. per ton.

[Ans. Speed-time curve : { Time (sec.) . . . 19·6 23·2 26·2 32·5* 65·1† 76·2
Speed (ml.p.h.) . . . 18·7 21·5 22·9 25·5 22·2 0
Energy consumption :—82·6 watt hours per ton mile.]

47. Under actual service conditions the train of the preceding example operates on a graded straight track with stations at the same level. The profile of the track between centres of station platforms, in the direction of running, is as follows :—

210 ft. level ; 240 ft. 1 in 30 down ; 870 ft. level ; 480 ft. 1 in 60 up ; 210 ft. level.

Calculate the speed-time curve and energy consumption of the train for the actual running conditions, assuming data as above.

[Ans. Speed-time curve : { Time (sec.) . . . 18 20 23·1 28·5* 43·2 53·2 58·9 67·2† 76·2
Speed (ml.p.h.) . . . 18·7 21·1 24 27·1 25·6 22·9 20·4 18 0
Energy consumption :—71·8 watt hours per ton mile.]

TRACK-WORK AND OVERHEAD CONSTRUCTION.—CHAPTERS XXIII–XXV

48. Sketch and describe a good method for supporting a third rail ‡ in the case of a continuous-current traction system, and indicate its position relative to the running rails. State approximately the electrical conductivity of each of the above types of rail, and the weight in lb. per yard run. (*L. U.* 1914.)

49. A double line of tramways, with an overhead trolley wire for each line, in streets 60 ft. wide, changes its direction through a right angle. Poles between tracks being prohibited, sketch the method you would propose for supporting the trolley wires round the curve. (*I. E. E.* 1914.)

50. Describe the construction of an overhead system of single-phase traction with special reference to some good method for neutralising the fall of voltage occurring in the line and the return rails. Give reasons for the special importance of this drop of voltage in alternating-current traction. (*L. U.* 1913.)

51. What is meant by “catenary suspension” in electric traction ? Point out its advantages and disadvantages compared with other methods of effecting the same purpose. Give a sketch of a modern arrangement. (*L. U.* 1911.)

52. Give details of the construction of a catenary suspension for a 6000-volt single-phase overhead line, and also of a suitable bow collector. (*L. U.* 1915.)

* Power off.

† Brakes applied.

‡ I.e. a conductor rail.

FEEDING AND DISTRIBUTING SYSTEMS.—CHAPTER XXVI

53. What are the Board of Trade regulations as affecting variation of declared voltage at consumer's terminals on public supply systems, and the allowable drop in voltage in the rails of tramway systems? In the latter case show what can be done to comply with these regulations when the voltage drop would otherwise exceed the limit allowed. (*L. U.* 1914.)

54. Discuss the causes of electrolytic corrosion of pipes arising from stray currents from a traction system in a large town. What precautions should be adopted to minimise corrosion (*a*) in matters relating to the pipes, (*b*) in matters relating to the traction system. Show how a negative booster should be connected and operated to reduce stray currents. (*C. & G.* 1913.)

55. In a town with an alternating-current supply of electricity for lighting and a continuous-current supply for a tramway, the tram rails forming the earthed return, the tramway runs for some distance close beside a railway. During Saturday afternoon football traffic it is found that the signalling track circuits on the railway, worked at 2 volts from a battery and using the earth for the return, are interfered with but at no other time. Describe why this is so, and suggest the remedy. (*I. E. E.* 1914.)

56. A double track tramway, $2\frac{1}{4}$ miles long, is loaded at the rate of 400 kw. per mile. Assuming the sub-station at one end of the road, show a system of negative feeding which will keep the rail drop under 3 volts. The resistance of the two tracks, including bonds, may be taken as 0.005 ohm per mile. (*C. & G.* 1915.)

57. A fault occurs on a conduit tramway system supplied through section feeders. How would you determine at the station whether it is on the main conductors or on the car? If on the car, show how it is possible to ascertain quickly (*a*) whether the fault is a dead earth or a partial one, (*b*) whether on the positive or the negative side, or (*c*) between conductors without earth. (*L. U.* 1909.)

58. In a tramway station in a small town taking its supply from a power company, state how you would determine the position of the sub-station to give the greatest economy in the feeders, and the arrangements you would make to secure an even distribution of potential in the trolley sections. What arrangements would you make to minimise stray currents in the ground. (*C. & G.* 1914.)

59. A continuous-current railway line (double track), ten miles long, with the trains on each track spaced one mile apart, requires an average supply of power of 6000 kw. at 600 volts. The generating station can only be placed at one end. What alternating-current voltage and frequency will you adopt for the transmission, where will you put the sub-stations, and what sizes of feeders and other conductors will you use so as to get the greatest economy in annual cost? Assume that the daily average supply of energy to the trains is 80,000 kw.-hours, and that a kw.-hour can be produced at the power house for $\frac{1}{4}$ d. (*C. & G.* 1915.)

SUB-STATIONS.—CHAPTER XXVII

60. A rotary converter with six slip rings is fed from the secondaries of a three-phase transformer with star-connected primaries. Each primary coil has ten times as many turns as the secondary. A load of 200 amperes at 500 volts is taken from the continuous-current side. Draw carefully a diagram of the connections, and also a vector diagram showing the magnitude and phase relationship of the voltages of the line, of the transformer coils, and of the slip rings. Calculate the approximate voltages on the mains and the currents in the primary coils. (Assume the efficiency to be 100 per cent. and the power-factor unity.) (*L. U.* 1914.)

[Ans. Voltage at slip rings (diametrical), 353; line voltage, 6100; current in primary coils, 9.46 amp.]

61. Give a diagram of connections for a sub-station with transformers and rotary converters for supplying power at 500 volts, continuous current, the primary supply being 10,000 volts, three phase. Calculate (a) the ratio of turns in the transformers, (b) the currents in their windings, and in the connections to the slip rings, when working at full load (1000 kw.) with a power-factor of 0.95. (*L. U.* 1912.)

[*Ans.*—(a) Ratio of turns ($\Delta-\Delta$)=32.6. (b) Current in primary windings =37.8 amp., current in secondary windings=1205 amp., current in connections to slip rings=2090 amp. (Assumed efficiencies : rotary converter, 95 per cent. ; transformers, 98 per cent.)]

62. Compare critically the following methods of starting rotary converters : (a) starting electrically from the continuous-current side, (b) starting electrically from the alternating-current side, (c) starting mechanically by a small motor. Consider the matter under the following headings : (d) ease of operation, (e) time taken to come into synchronism, (f) reliability in times of stress when generating voltage is unsteady. (*C. & G.* 1914.)

63. Describe the various methods used to start and synchronise a rotary converter in a traction sub-station. State the advantages and disadvantages of each method. (*C. & G.* 1916.)

64. What apparatus is contained on a Board of Trade panel in a traction supply station ? Explain the tests carried out and point out the object of each. (*L. U.* 1910.)

65. A tramway sub-station having an output of 1500 kw. at 600 volts is supplied with power at 6000 volts from three-phase mains. Make a careful diagram of the connections, and show a suitable arrangement of the sub-station plant. (*L. U.* 1913.)

66. A railway working on a 600-volt continuous-current system has sub-stations spaced five miles apart. The pressure drop midway between feeding points is found to be excessive. What methods would you propose for improving the regulation ? If additional sub-stations are erected, where would they be placed, and what plant would be installed in them ? Give sketches of the arrangements in a sub-station suitable for handling a peak load of 2000 kilowatts. (*C. & G.* 1916.)

67. A suburban railway about twenty miles in length has a regular service of stopping trains and occasional non-stop trains, both of the multiple-unit-controlled motor-coach type. Current is supplied to the trains through conductor rails from rotary converter sub-stations supplied from a three-phase generating station at 11,000 volts between conductors. Discuss the separate efficiencies and the overall efficiency you would expect to obtain between the high-tension switchboard in the generating station and the motor-driven axles of the train : (a) For the frequent stopping service, (b) for the infrequent stopping service. (*I. E. E.* 1914.)

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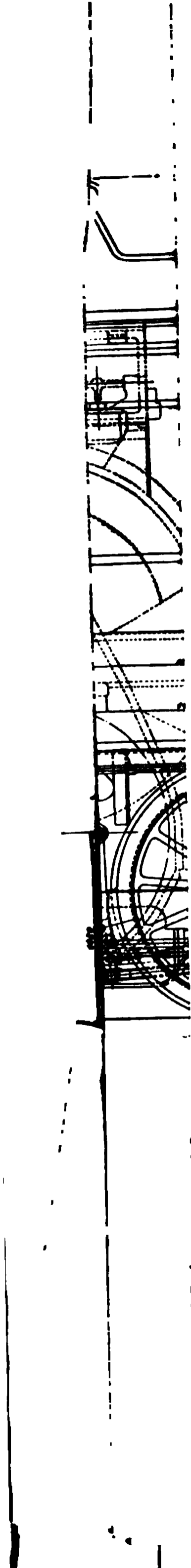
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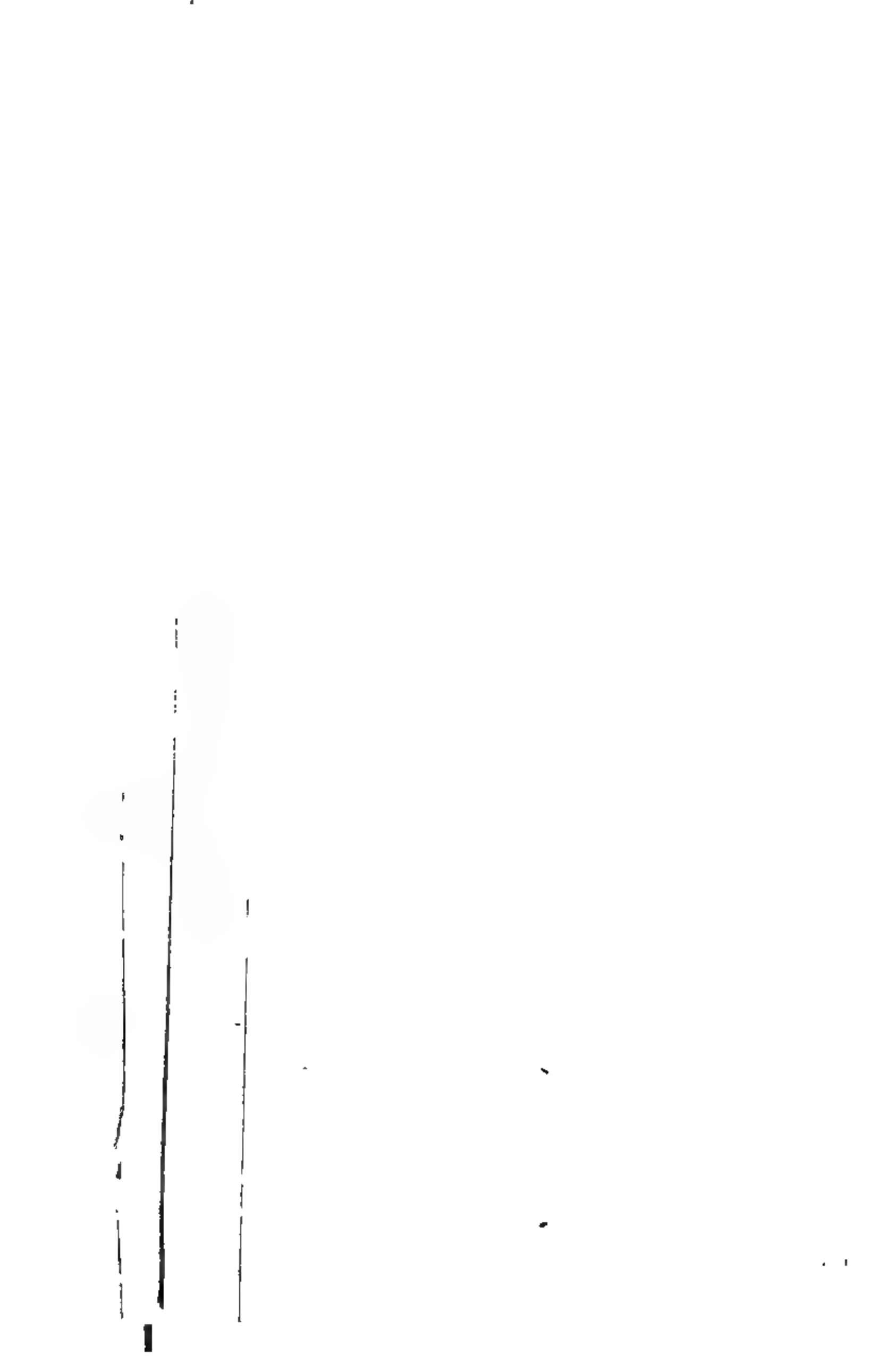
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1

[PLATE III]



1,300				
140				
PRINCIPAL DATA				
over buffers	.	.	.	4' 8 $\frac{1}{2}$ "
base	.	.	.	11,840 mm. (38' 1")
base	.	.	.	8,000 mm. (26' 3")
driving wheels	.	.	.	4,800 mm. (15' 1")
crank-pin circle	.	.	.	1,250 mm. (49.2")
t (adhesive)	.	.	.	560 mm. (22")
mechanical equipment	.	.	.	67 tons
electrical equipment	.	.	.	32.4 tons
at (1 hour)	1,100	1,300	1,500	1,700 H.P.
	(16 poles)	(12 poles)	(8 poles)	(6 poles)
ort at rated output	25,400	22,300	17,000	14,000 lb.
ponding to rated output	16.2	21.8	33	44.2 ml.p.h.
	.	.	.	3,000
ge	.	.	.	3,000
	.	.	.	15

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